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Building a simulation toolkit for wireless mesh clusters and evaluating the suitability of different families of ad hoc protocols for the Tactical Network Topology

Karapetsas, Konstantinos

Monterey, California. Naval Postgraduate School

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MONTEREY, CALIFORNIA

THESIS

BUILDING A SIMULATION TOOLKIT FOR WIRELESS MESH CLUSTERS AND EVALUATING THE SUITABILITY OF DIFFERENT FAMILIES OF AD HOC PROTOCOLS FOR THE TACTICAL NETWORK TOPOLOGY

by

Konstantinos Karapetsas

March 2005

Thesis Co-Advisor: Alexander Bordetsky
Thesis Co-Advisor: Gilbert M. Lundy

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Wireless mesh networking has emerged as the successor of the traditional ad hoc networks. New technological advances, the standardization of protocols and interfaces and the maturity of key components have made it possible for current mesh research groups to set goals that are really close to the world's expectations. The objective of this research is to design and implement a simulation toolkit for wireless mesh clusters that can be used as an additional performance evaluation technique for the Tactical Network Topology program of Naval Postgraduate School. This toolkit is implemented in the OPNET simulation environment and it incorporates various nodes running different ad hoc routing protocols. Furthermore, the investigation of a suitable combination of protocols for the Tactical Network Topology is achieved by creating scenarios and running a number of simulations using the mesh toolkit.

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Konstantinos Karapetsas
Captain, Hellenic Air Force
M.Sc., Technical University of Crete, 2002

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and
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from the

NAVAL POSTGRADUATE SCHOOL
March 2005

Author: Konstantinos Karapetsas

Approved by: Alexander Bordetsky
Thesis Co-Advisor

Gilbert M. Lundy
Thesis Co-Advisor

Dan Boger
Chairman, Department of Information Sciences

Peter J. Denning
Chairman, Department of Computer Science

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Wireless mesh networking has emerged as the successor of the traditional ad hoc networks. New technological advances, the standardization of protocols and interfaces and the maturity of key components have made it possible for current mesh research groups to set goals that are really close to the world's expectations. The objective of this research is to design and implement a simulation toolkit for wireless mesh clusters that can be used as an additional performance evaluation technique for the Tactical Network Topology program of Naval Postgraduate School. This toolkit is implemented in the OPNET simulation environment and it incorporates various nodes running different ad hoc routing protocols. Furthermore, the investigation of a suitable combination of protocols for the Tactical Network Topology is achieved by creating scenarios and running a number of simulations using the mesh toolkit.

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TABLE OF CONTENTS

I. INTRODUCTION....1
A. BACKGROUND....1
B. OBJECTIVES....1
C. RESEARCH QUESTIONS....2
D. SCOPE....2
E. METHODOLOGY....2
F. THESIS ORGANIZATION....3

II. WIRELESS MESH NETWORKING....5
A. AD HOC NETWORKS....5
B. EVOLUTION OF AD HOC NETWORKING....6
C. MESH CHARACTERISTICS....11
D. CONSIDERATIONS AND CHALLENGES....11
1. Physical Layer....12
2. Media Access Control....12
3. Routing....15
4. TCP Congestion Control and Mobility....16
5. Power Management....17
6. Security....18
7. Other Challenges....18
E. NETWORK LAYER PROTOCOLS....18
1. OLSR....21
2. DSR....22
3. AODV....22
F. COMPARATIVE STUDIES OF ROUTING PROTOCOLS....23

III. TOOLKIT IMPLEMENTATION....27
A. INITIAL DESIGN CONSIDERATIONS....27
B. MODELLING ENVIRONMENT....28
1. Simulation Programs....28
2. Our Choice....29
C. TOOLBAR CREATION....31
D. LAPTOP MOBILE AND FIXED NODES....34
1. OLSR....34
2. DSR....36
3. AODV....38
E. SENSOR NODES....39
F. CONCLUSION....41

IV. SIMULATION ANALYSIS....45
A. TOOLKIT USAGE....45
B. THE TNT PROJECT....45
C. IEEE 802.16 AND DOCSIS....47
1. DOCSIS Concept....48

2. OPNET Model Creation....49
D. SIMULATION OVERVIEW....51
1. Goal Definition and System Description....51
2. Metrics....52
3. Parameters....52
4. Factors....54
5. Workload....54
6. Experimental Design....55
7. Data Presentation and Analysis....55
E. CONCLUSION....60
V. CONCLUSIONS....63
A. OVERVIEW....63
B. RECOMMENDATIONS FOR FUTURE RESEARCH....64
APPENDIX. FILES REMOVED FROM THE OPNET PROTOCOL PACKAGES....65
A. OLSR....65
B. DSR....65
C. AODV....67
LIST OF REFERENCES....69
INITIAL DISTRIBUTION LIST....77

LIST OF FIGURES

Figure 1. Representation of an ad hoc network 5
Figure 2. Network architecture of PRNET (From Toh 2002, 16) 7
Figure 3. Point-To-Multipoint and mesh approach 10
Figure 4. The hidden terminal problem (After Liu and Chlmtac 2004, 19) 13
Figure 5. RTS/CTS solution to hidden terminal problem (After Toh 2002, 41) 14
Figure 6. The exposed node problem (After Liu and Chlamtac 2004, 19 and Toh 2002, 45) 14
Figure 7. Overview of ad hoc routing protocols (From Halvardsson and Lindberg 2004, 15) 20
Figure 8. OPNET model decomposition (After OPNET Training 2004, 4) 31
Figure 9. Toolbar file..33
Figure 10. Toolbar contents...33
Figure 11. OLSR laptop node derivation 35
Figure 12. OLSR PDA node derivation 36
Figure 13. DSR laptop node derivation...37
Figure 14. DSR PDA node derivation...37
Figure 15. AODV laptop node derivation...38
Figure 16. AODV PDA node derivation...39
Figure 17. Sensor node derivation..40
Figure 18. Example scenario of sensor connectivity to mesh cluster 41
Figure 19. Final version of toolbar file..42
Figure 20. Final version of toolbar contents...43
Figure 21. TNT mesh topology and IEEE 802.16...46
Figure 22. IEEE 802.16 architecture (From IEEE C802.16-02/09 2002, 7)......................47
Figure 23. DOCSIS node derivation 49
Figure 24. DOCSIS interfaces addition to node..50
Figure 25. Simulation “environment” definition..51
Figure 26. Mobility patterns...53
Figure 27. IP traffic flows between mesh clusters 55
Figure 28. Routing traffic sent and received 57
Figure 29. Route discovery time and average number of hops per route in reactive protocols...58
Figure 30. Average load on wireless LAN..59
Figure 31. Throughput performance 60

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LIST OF TABLES

Table 1. Power conservation techniques at protocol layer (From Toh 2002, 156)........17
Table 2. System and workload parameters 53
Table 3. Individual node's traffic generation parameters 54
Table 4. Files removed from the OLSR protocol package 65
Table 5. Files removed from the DSR protocol package...66
Table 6. Files removed from the AODV protocol package 67

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LIST OF ABBREVIATIONS AND ACRONYMS

ABR	Associativity Based Routing
ACK	Acknowledgement
ACPI	Advanced Configuration and Power Interface
ADV	Adaptive Distance Vector
AFIT	Air Force Institute of Technology
AODV	Ad hoc On-demand Distance Vector
AODV-BR	AODV with Backup Routes
AOMDV	Ad hoc On-demand Multipath Distance Vector
APM	Advanced Power Management
APRL	Any Path Routing without Loops
ARAN	Authenticated Routing for Ad hoc Networks
BRP	Bordercast Resolution Protocol
BS	Base Station
CBRP	Cluster Based Routing Protocol
CGSR	Clusterhead-Gateway Switch Routing
CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
DAMA	Demand Assigned Multiple Access
DARPA	Defense Advanced Research Projects Agency
DBF	Distributed Bellman-Ford
DBTMA	Dual Busy Tone Multiple Access
DCF	Distributed Coordination Function
DNS	Domain Name Server

DOCSIS	Data Over Cable Service Interface Specifications
DoD	Department of Defense
DoS	Denial of Service
DSDV	Destination-Sequenced Distance Vector
DSR	Dynamic Source Routing
EADSR	Energy Aware Dynamic Source Routing protocol
EAP	Energy Aware Protocol
FAMA	Floor Acquisition Multiple Access
FSM	Finite State Machine
GAF	Geographical Adaptive Fidelity
GloMoSim	Global Mobile Information Systems Simulation Library
GPS	Global Positioning System
HMMWV	High-Mobility Multipurpose Wheeled Vehicles
IARP	Intrazone Routing Protocol
IEEE	Institute of Electrical and Electronics Engineers
IERP	Interzone Routing Protocol
IETF	Internet Engineering Task Force
IP	Internet Protocol
IS	Information Sciences
ISM	Industrial, Scientific and Medical
LAN	Local Area Network
LANMAR	Landmark Routing Protocol for Large Scale Networks
LAR	Location-Aided Routing
MAC	Media Access Control

MACA	Multiple Access with Collision Avoidance
MACA/PR	Multiple Access Collision Avoidance with Piggyback Reservation
MACA-BI	MACA By Invitation
MACAW	Multiple Access with Collision Avoidance for Wireless
MANET	Mobile Ad hoc Network
MAODV	Multicast AODV
MPR	Multi-Point Relays
NIST	National Institute of Standards and Technology
NLOS	Non Line-Of-Sight
NPS	Naval Postgraduate School
ODMRP	On-Demand Multicast Routing Protocol
OFDM	Orthogonal Frequency Division Multiplexing
OLSR	Optimized Link State Routing
OPNET	Optimized Network Engineering Tool
OS	Operating System
PAMAS	Power-Aware Multi-Access protocol with Signaling
PAODV	Preemptive Ad hoc On-demand Distance Vector
PARSEC	Parallel Simulation Environment for Complex Systems
PDA	Personalized Digital Assistant
PHY	Physical Layer
PMP	Point-to-Multipoint
PRNET	Packet Radio Network
PTP	Point-to-Point
QOLSR	Quality of Service for Optimized Link State Routing

QoS	Quality of Service
RF	Radio Frequency
RFC	Request For Comments
RREP	Route Reply
RREQ	Route Request
RTS/CTS	Request to Sent/ Clear to Send
RTT	Round-Trip Time
SATCOM	Tactical Satellite
SRP	Secure Routing Protocol
SS	Subscriber Station
SSR	Signal Stability Routing
STAR	Source Tree Adaptive Routing
STARA	System- and Traffic-dependent Adaptive Routing Algorithm
TBRPF	Topology Broadcast based on Reverse-Path Forwarding
TCP	Transmission Control Protocol
TCP-F	TCP Feedback
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TNT	Tactical Network Topology
TORA	Temporally-Ordered Routing Algorithm
UAV	Unmanned Arial Vehicle
USN	United States Navy
VoIP	Voice over IP
WARP	Wireless Ad Hoc Routing Protocol

WCTG	Wireless Communication Technologies Group
WLAN	Wireless Local Area Network
WRP	Wireless Routing Protocol
ZRP	Zone Routing Protocol

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I. INTRODUCTION

A. BACKGROUND

The concept of ad hoc networking and infrastructureless communication has been around for over three decades. The intriguing characteristics of these networks that sustained them in the focus of the research community for so long include their ability to form dynamically, to organize themselves without any central administration point and to support rapid and unpredictable topology changes. The emergence of new technological advances, the standardization of protocols and interfaces and the maturity of key components have made it possible for current ad hoc research groups to set goals that are really close to the world's expectations.

B. OBJECTIVES

The primary objective of this study is to provide an additional performance evaluation technique for the TNT program of Naval Postgraduate School. The current approach involves field experiments and measurements of existing systems. The goal of this research is to add a simulation capability in the form of a network simulation toolkit for mobile mesh clusters.

The benefits of having a simulation toolkit are threefold. First, simulation tools can address scalability challenges more effectively than actual measurements. Field experiments are limited by the number of nodes used and also, the process of planning for hundreds of sensors and wireless, mobile units requires simulation modeling tools. Second, the use of two techniques simultaneously can be helpful in verifying and validating the results of each one. A simulation model combined with existing and future experiments can provide a very robust framework for analyzing results. Finally, the time, effort and cost for planning and executing real measurements are significantly greater than running simulations, especially in the case that we need to investigate "what-if" scenarios.

The second goal of this research is to evaluate the suitability of different families of ad hoc protocols for the Tactical Network Topology. The desired outcome would be to have the ability to determine an effective combination of ad hoc routing protocols for a given scenario.

The benefits of this objective are straightforward. Having a simulation tool to test and decide on particular combinations depending on the scenario could prove beneficial for the planning effort needed by real experiments.

C. RESEARCH QUESTIONS

The main research questions of this study are the following:

- Why modeling wireless mesh clusters is important?
- What is an appropriate model design for the nodes of a heterogeneous wireless mesh cluster?
- What are the distinct characteristics of each wireless node that should be taken under consideration in the modeling task?
- What are the criteria for determining the suitability of different protocols for the TNT project?
- What is an efficient combination of wireless mesh routing protocols for the TNT network?

D. SCOPE

The study area of this thesis will be the modeling of wireless mesh nodes and the evaluation of the suitability of different families of ad hoc protocols for the Tactical Network Topology. The majority of ad hoc routing protocols have been modeled successfully by many organizations and universities. Our study will use these models to build the mesh nodes and to add their distinct functions and characteristics.

Also, the evaluation of the suitability of different categories of ad hoc protocols will be based on the model of mesh nodes. There is a lot of bibliography and research towards comparative studies of these categories. This thesis will be focused on the specific needs of the Tactical Network Topology.

E. METHODOLOGY

The modeling of the wireless mesh nodes will be based on the existing OPNET models and the process modeling methodology (PMM) provided by the OPNET software. The OPNET process modeling methodology includes the design and

implementation part. The design stage is the most critical task and can be viewed as an iterative process. The implementation part is straightforward and will produce the wireless mesh toolkit. Finally, the evaluation of different categories of ad hoc protocols will be conducted using OPNET's discrete event simulation capabilities and the wireless mesh toolkit.

F. THESIS ORGANIZATION

The organization of the thesis is as follows:

Chapter II provides an overview of the evolution of mobile ad hoc networks and describes the concept of wireless mesh clusters. Also, it introduces the families of ad hoc routing protocols and provides a more detailed explanation of the protocols that are going to be presented in this study. Finally, it addresses the issues of existing comparative studies between different families of protocols.

Chapter III begins with the design considerations of the mesh toolkit and continues with a short description of OPNET, the software tool used for modeling the mesh nodes. The main part of this chapter includes the implementation details for each node of the wireless mesh toolkit.

Chapter IV identifies the distinct characteristics of the TNT environment and the relation of these key features with the mesh simulation scenarios. Furthermore, it describes the usage of the wireless mesh toolkit to test different scenarios and to draw certain conclusions about an effective combination of different families of ad hoc routing protocols.

Chapter V includes our conclusions from the modeling task and the simulation runs. Recommendations for future research are also included.

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II. WIRELESS MESH NETWORKING

A. AD HOC NETWORKS

The work on ad hoc networking has been the basis for wireless mesh networks. The definition of ad hoc networking is closely related to infrastructureless communication. For example, Peterson and Davie (2003, 299) refer to ad hoc mobile networks as “a group of mobile nodes that form a network in the absence of any fixed nodes” while Kurose and Ross (2005, 507) highlight the fact that “in ad hoc networks, wireless hosts have no such infrastructure with which to connect. In the absence of such infrastructure, the hosts themselves must provide for services such as routing, address assignment, DNS-like name translation, and more.” Also, Toh (2002, 27) provides his insight on the term “ad hoc” as “can take different forms” and “can be mobile, standalone, or networked.” His formal definition of ad hoc networks is “a collection of two or more devices equipped with wireless communications and networking capability. Such devices can communicate within another node that is immediately within their radio range or one that is outside their radio range. For the latter scenario, an intermediate node is used to relay of forward the packet from the source toward the destination” (Toh 2002). Figure 1 illustrates an ad hoc network based on the above observations.

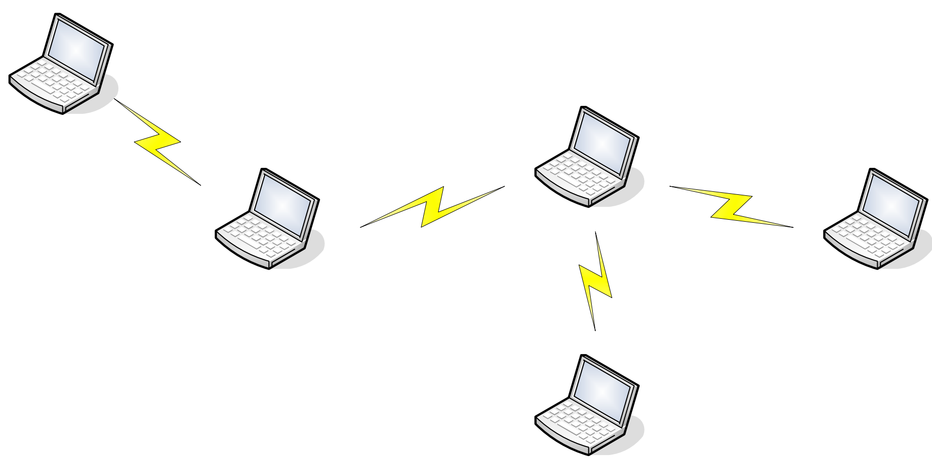


Figure 1. Representation of an ad hoc network

Many authors define ad hoc networks in the context of the enabling technology, namely IEEE 802.11 wireless LAN, also known as Wi-Fi. Stallings (2002, 437) explains

that an ad hoc wireless LAN is “a peer-to-peer network (no centralized server) set up temporarily to meet some immediate need” and concludes that “there is no infrastructure for an ad hoc network. Rather, a peer collection of stations within range of each other may dynamically configure themselves into a temporary network.” Moreover, Kurose and Rose (2005, 514) add that “IEEE 802.11 stations can also group themselves to form an ad hoc network – a network with no central control and with no connections to the “outside world.” Here, the network is formed “on the fly”, by mobile devices that have found themselves in proximity to each other, that have a need to communicate, and that find no preexisting network infrastructure in their location.” These definitions incorporate the basic infrastructureless notion but also, address range considerations related to the IEEE standard 802.11.

The aforementioned elements of ad hoc networking are the foundations that supported the work for MANETs and wireless mesh networks. These networks and their differences are further analyzed in the following paragraph that exhibits the major events in the history of ad hoc networking.

Overall, the literature identifies a number of distinct elements that identify ad hoc networks. The most prevalent characteristics include the lack of supporting infrastructure, the lack of centralized control or administration, the routing capability of individual nodes and the dynamic configuration of nodes (“on the fly”).

B. EVOLUTION OF AD HOC NETWORKING

The idea of ad hoc networking dates back to the early 1970s (Toh 2002, Zaruba and Das 2004). At that time there was a great interest by the US Department of Defense in survivable, infrastructureless and less detectable military communications and networks. In 1972, DARPA initiated a new project known as packet radio network (PRNET). This program was based on the packet radio technology which linked packet switching with broadcast radio networks. The broadcasting capability of radios in a single radio hop system was exhibited two years earlier by the ALOHA project at the University of Hawaii (Zaruba and Das 2004, 48). This protocol was used to interconnect the network infrastructure of four Hawaiian Islands with eight transceivers. The ALOHA project resulted in the implementation of a multi-hop PRNET which allowed communications over a wide geographical area (Toh 2002, 13). The architecture of this network (Figure 2)

included mobile radio repeaters, mobile stations and wireless terminals. The main function of the repeaters (represented by the HMMWVs in Figure 2) was simply to relay data packets from the source to the destination node. The mobile stations produced the routes from one station to another and since there was a constant change in the network conditions due to stations mobility, node failures and congestion rate, these stations were also empowered to dynamically recalculate the necessary routes. Finally, the terminals were considered as end nodes without any participation in the routing decisions.

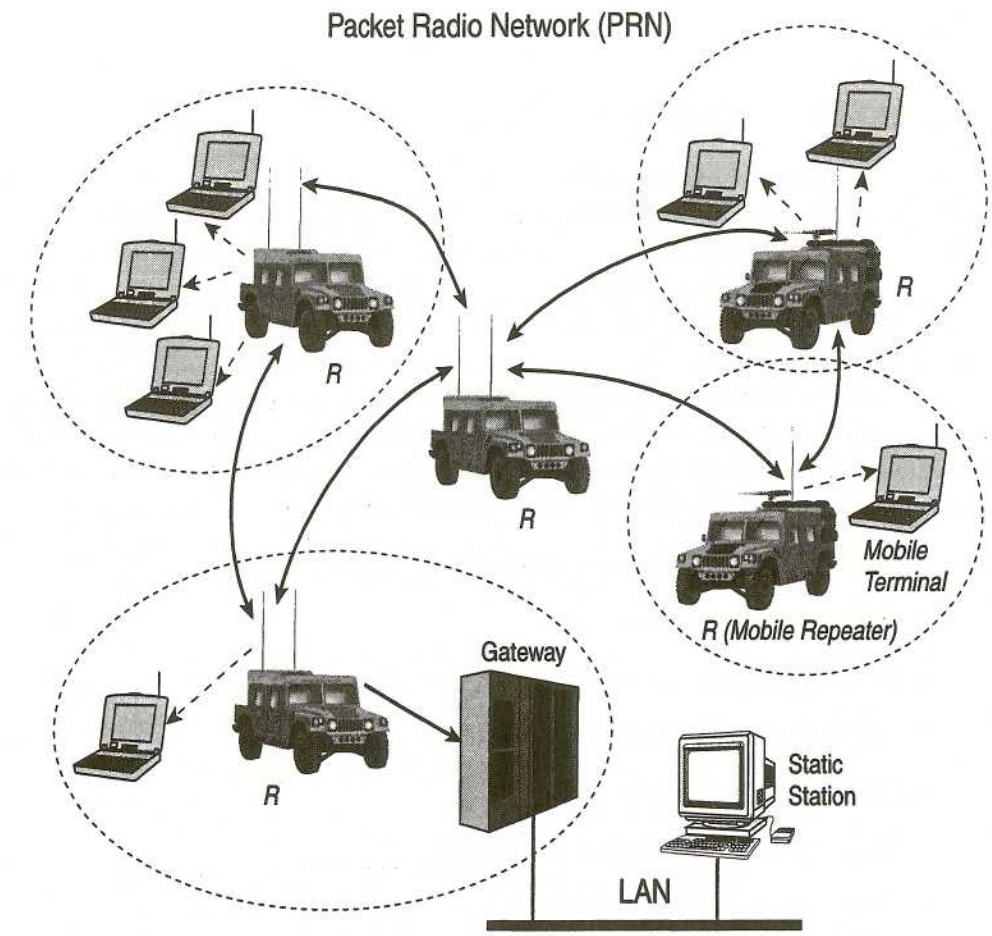


Figure 2. Network architecture of PRNET (From Toh 2002, 16)

The PRNET introduced a number of interesting technical challenges for ad hoc networking. Toh (2002, 15) identifies that the wireless medium and the mobility factor were the most important, but also enumerates a number of other elements such as flow and error control, routing derivation and physical characteristics (size, power and

processing capabilities). Especially for the routing considerations, PRNET supported point-to-point communications by point-to-point routing and also, implemented broadcast routing. The point-to-point paradigm means that a packet travels from a source node through a series of repeaters towards the destination. Broadcast routing is equivalent to flooding in wired networks and this has proved beneficial in the case of rapidly changing routes. Toh (2002, 18-19) underlines that "point-to-point routing may not be practical since most of the time will be spent in computing alternate point-to-point routes....Under such circumstances, very poor communication performance will be observed." The point-to-point and point-to-multipoint argument is very important in ad hoc networking and will be investigated later on in this section.

In the early 1980s, the PRNET project was replaced by the Survivable Radio Network (SURAN) which introduced improvements in the physical properties and the routing characteristics of PRNET (Zaruba and Das 2004, 48). At that time, DoD remained a key player in the research and development efforts of ad hoc networking. The commercial industry did not consider the related technology to be cost-effective and remained idle.

In the early 1990s, the research and engineering community started to have an increasing interest in ad hoc networks. The main reasons were the major growth experienced by the Internet, the declining cost of hardware and software and the growing power and capabilities of mobile devices. At that time, packet radio networks were renamed ad hoc networks and the old ad hoc related problems transformed to important research areas. The study of these networks created the need for supporting standardized technology and standardized protocols. The first requirement was addressed by the IEEE 802 Group. This group, which is responsible for computer communication networks, established the IEEE 802.11 subcommittee to standardize the wireless LAN technologies and to provide guidelines for uniform technological solutions. The IETF addressed the second requirement by establishing the MANET Working Group in 1997. The purpose of this group was to create and standardize new routing protocols that could handle the multi-hop dynamics of ad hoc networks. Moreover, the DoD pursued its interests in ad hoc networking by funding projects such as the Global Mobile Information Systems (GloMo) and Near-term Digital Radio (NTDR) in 1994 (Zaruba and Das 2004, 48). More

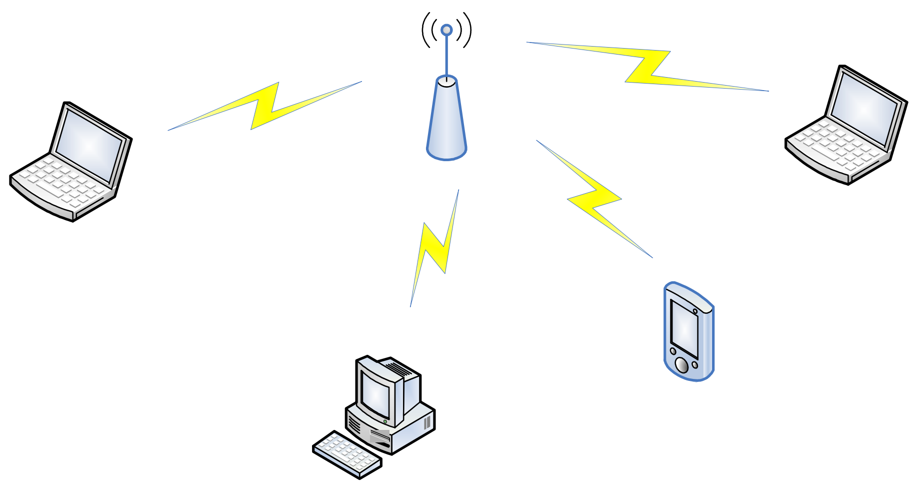
recent implementations included US Army Tactical Internet (TI) in 1997 and the Extending the Littoral Battlespace Advanced Concept Technology Demonstration (ELB ACTD) used by the US Marines in 1999.

At the beginning of the new century most of the literature used the term “mobile ad hoc networks” to describe the concepts of ad hoc networking. In addition, a number of synonyms or related terms appeared like “wireless ad hoc networks” or “ad hoc wireless networks” (NIST, “Wireless Ad Hoc Networks” webpage 2005), “multihop wireless ad hoc networks” (Liu and Chlamtac 2004), “ad hoc multihop wireless networks”, “mobile mesh networks” (Macker and Corson 2004) and “mobile, multihop wireless networks” (Macker and Corson 2004). Some of these names are intuitive regarding their relation to ad hoc networking while others add some new concepts like multihopping or mesh networking. As routes in MANETs can include multiple hops from source to destination, the use of the term “multihop” can be considered appropriate. The name “mobile mesh networks” appeared in an article in The Economist in the context of future military networks (Macker and Corson 2004, 299). Corson et al. (1996) states that “a "mobile mesh" network is an autonomous system of mobile routers connected by wireless links, the union of which forms an arbitrary graph. The routers are free to move randomly; thus, the network's wireless topology may change rapidly and unpredictably.”

In this context, mobile mesh networks can be considered as successors of ad hoc networks and MANETs. A more general term used is “wireless mesh network”, meaning a network that handles many-to-many connections (multipoint-to-multipoint) and is capable of dynamically updating and optimizing these connections. This may be a mobile network, but can also include wireless static nodes. The difference between the point-to-multipoint paradigm that was discussed earlier and the mesh approach is illustrated in Figure 3.

LAN." Essentially, MANETs are a subset of mesh networks.

Point-To-Multipoint Approach



Mesh Approach

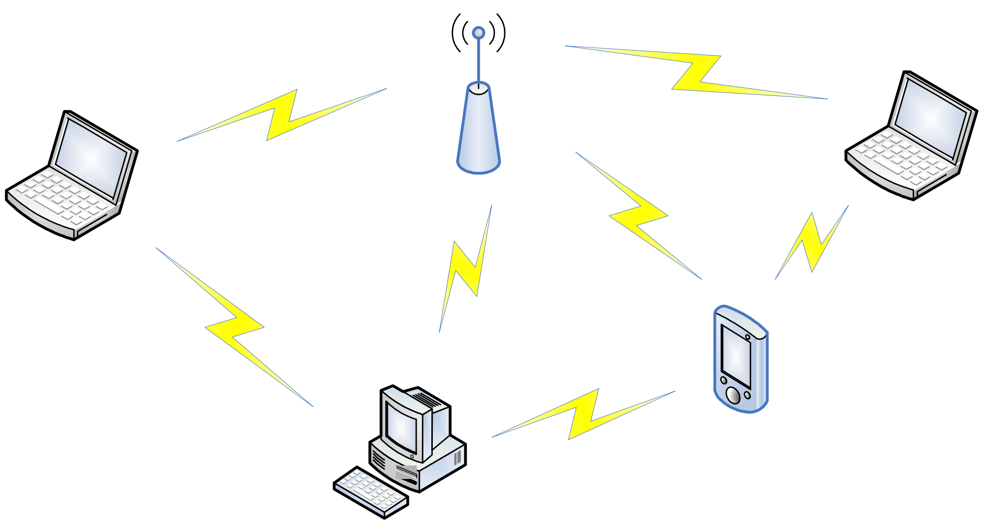


Figure 3. Point-To-Multipoint and mesh approach

Another definition given by Wikipedia ("Wireless Mesh Network" webpage 2005) is "wireless mesh networking is mesh networking implemented over a Wireless LAN." Essentially, MANETs are a subset of mesh networks.

C. MESH CHARACTERISTICS

The wireless mesh approach inherits the beneficial characteristics of ad hoc networks. Elliott and Heal (2000) describe ad hoc networks as self-organizing and self-healing. These two concepts refer to the fact that "every node in such a network has sufficient intelligence to continuously sense and discover other nearby nodes, dynamically determine the optimal path for forwarding data packets from itself hop by hop through the network to any other node in the network, and automatically heal any ruptures in the network fabric that are caused by ongoing movement of the nodes themselves, changes in RF propagation, destruction of nodes, etc." (Elliott and Heal 2000). Toh (2002) adds that ad hoc networks are adaptive. This concept is closely related to the fact that ad hoc networks can be formed "on the fly" without the need for coordination or administration, can detect and identify nearby stations and finally, establish connection to allow communication and information sharing. The "on the fly" configuration is also referred to as the self-forming characteristic. Moreover, ad hoc networks can be formed from various types of wireless devices (for example, laptops, PDAs, sensors, mobile phones, etc.). In other words, ad hoc networking supports heterogeneity (Toh 2002, 28).

Except from the above inherited features, wireless mesh networks exhibit their own significant characteristics. One of the most prominent is fault tolerance since the mesh structure is constructed by redundant connections. In addition, Beyer (2002) states that mesh coverage and robustness improves exponentially as subscribers are added. Also, the same author argues that mesh networks are highly extendable and easy to seed creating fast area coverage with only a few stations. Finally, increasing device density increases overall network capacity and stability.

D. CONSIDERATIONS AND CHALLENGES

The distinct characteristics of wireless mesh networks make them more flexible and agile but also, introduce a number of considerations and technological challenges. Some of these issues are related to the wireless medium, others are inherited by known MANET challenges and the rest have emerged from the mesh approach.

1. Physical Layer

The important issues in this layer are the wireless link characteristics, the wireless node limitations and the band used for ad hoc networks. The wireless medium has significant differences from the wired infrastructure. Kurose and Ross (2005) identify that the wireless environment experiences decreasing signal strength due to attenuation (also referred to as path loss), interference from other sources and multipath propagation due to electromagnetic wave reflections off various objects. All these can cause higher loss rates and potentially higher delays and jitter. The wireless nodes can have different processing capabilities and varying transmitting and receiving power and range (Liu and Chlamtac 2004, Macker and Corson 2004). This can create asymmetric links that are difficult to plan for and deal with. Finally, most ad hoc networks are currently implemented in the ISM band along with other devices (Toh, 2002). This promotes channel interference which brings all the negative results described earlier.

2. Media Access Control

Mesh nodes share the wireless medium and are able to access the common channel at the same time. Without the presence of a static central coordinating node, the MAC protocol should be able to employ an efficient and fast contention resolution mechanism. This need is even greater if we consider that mesh clusters incorporate mobility and frequent topological changes. The design of a MAC protocol is further constrained by the presence of two additional problems, namely hidden terminals and exposed nodes (Toh 2002, 35).

The hidden terminal problem and the exposed nodes are extensively documented in the literature (for example, Elliott and Heile (2000), Toh (2002), Peterson and Davie (2003), Liu and Chlamtac (2004), Kurose and Ross (2005) and many more). Toh (2002, 40) states that “two nodes are said to be hidden from one another (out of signal range) when both attempt to send information to the same receiving node, resulting in a collision of data at the receiving node.” In Figure 4, node A and C are hidden from each other and a collision may occur if both nodes start transmitting towards the same receiver B.

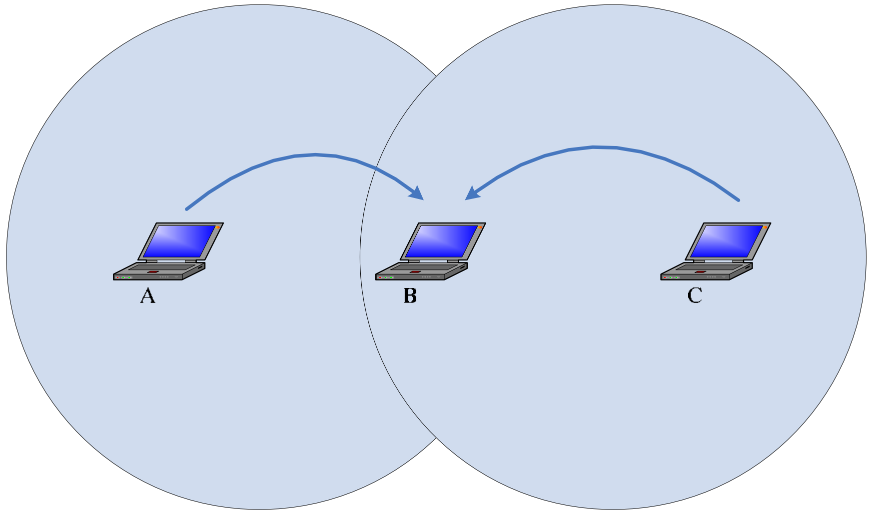


Figure 4. The hidden terminal problem (After Liu and Chlmtac 2004, 19)

Elliott and Heile (2000) underline that there are a number of solutions suggested for the hidden terminal problem, but the most popular is the RTS/CTS approach. According to this solution, a station sends a request to send (RTS) data to another node. The receiving station informs (CTS) all of its neighboring stations that the channel will be busy until further notice (ACK). In this way, it prevents simultaneous transmissions and potential collisions. This process is illustrated in the Figure 5.

The RTS/CTS does not solve all the possible scenarios that can lead to hidden terminal problems. In some cases collisions happen when the RTS and CTS messages are sent by different stations or when more than one CTS messages are transmitted to different neighboring nodes (Toh 2002, 42).

Liu and Chlamtac (2004) state that the exposed node problem "results from situations in which a permissible transmission from a mobile station (sender) to another station has to be delayed due to the irrelevant transmission activity between two other mobile stations within sender's transmission range." This situation is illustrated in Figure 6.

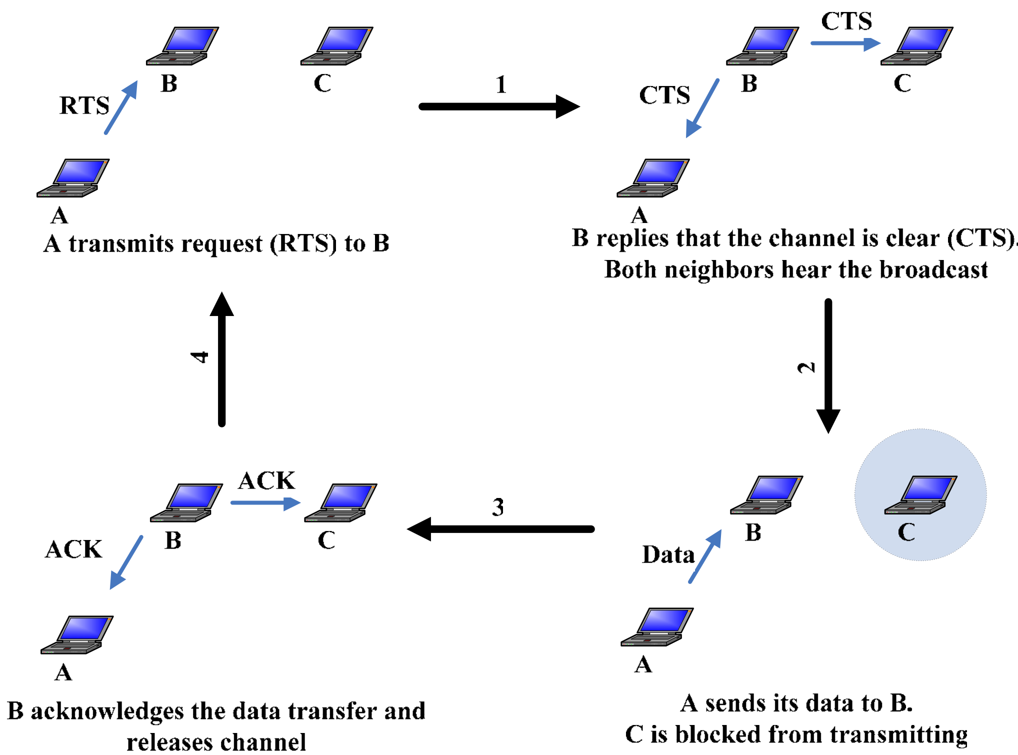


Figure 5. RTS/CTS solution to hidden terminal problem (After Toh 2002, 41)

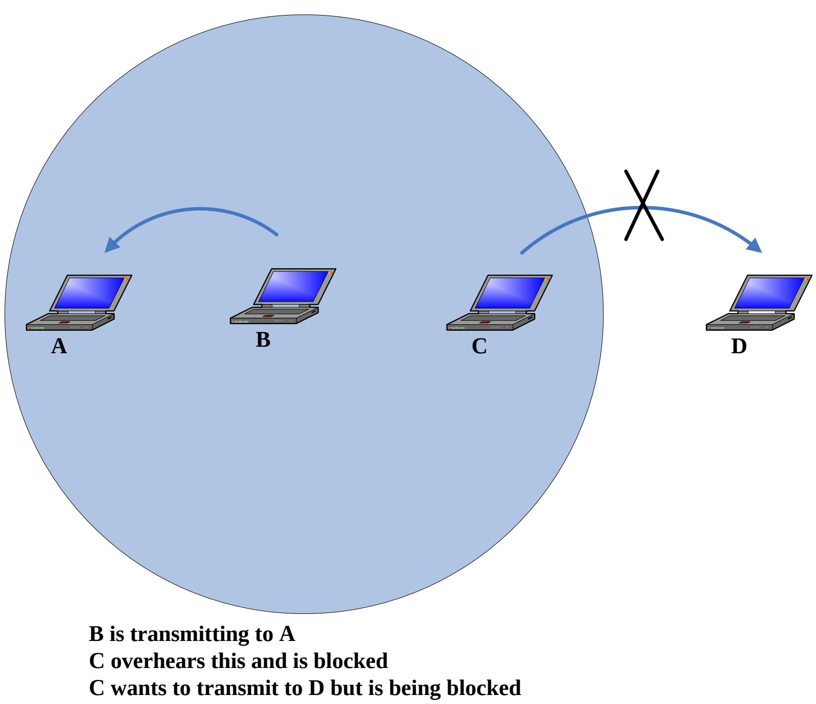


Figure 6. The exposed node problem (After Liu and Chlamtac 2004, 19 and Toh 2002, 45)

A solution to the exposed node problem is the use of different control and data channels or the use of directional antennas. Examples of the first case are the PAMAS and DBTMA protocols. Toh (2002) illustrates how these approaches succeed in solving the problem.

In order to address all the above MAC issues the research community proposed a number of MAC ad hoc protocols, such as MACA, MACAW (MACA with acknowledgement), FAMA, MACA/PR and MACA-BI, to resolve the various problems and to improve channel performance. Toh (2000) groups these protocols in two categories: (a) receiver-initiated which includes MACA-BI and (b) sender-initiated which includes MACA, MACAW and FAMA. In IEEE 802.11, the MAC layer uses the CSMA/CA mechanism, a variation of the MACA protocol, and DCF to provide collision avoidance and congestion control (IEEE Std. 802.11-1997). A further analysis of these protocols is beyond the scope of this study.

3. Routing

The mobility factor of the wireless mesh clusters is the main concern for ad hoc routing protocols. Existing distance vector and link state approaches used in wired infrastructures have proven inadequate in coping with constant link and topological changes that result in “poor route convergence and very low communication throughput” (Toh 2002, 35). Also, there are other factors that should be taken under consideration such as resource-limited stations, low bandwidth, high error rates, “selfish nodes” (Liu and Chlamtac 2004, 17) and others. All these characteristics drive the design goals for more efficient and robust routing protocols.

Belding-Royer (2004) describes a number of desirable characteristics for an ad hoc routing protocol:

- Minimal control overhead to avoid increased number of messages that consume bandwidth and power resources.
- Minimal processing requirements that can be achieved through smart algorithms.
- Ability to handle multihop routing.
- Handling of frequent topological changes.
- Preventing loops in the network paths.

Over the years, numerous protocol implementations have been suggested for ad hoc networking. Many of these protocols demonstrate common features and form distinct categories or families of protocols. A more detailed analysis of existing classes of ad hoc routing protocols will be provided later on in this chapter.

4. TCP Congestion Control and Mobility

The main idea behind the TCP congestion control mechanism is for each source node to identify and continuously update the information regarding available network capacity. This is necessary in order for each node to know how many packets it can safely send over the network. Peterson and Davie (2003, 468) state that the source nodes use ACKs to organize the transmission of packets and this is the reason that "TCP is said to be self-clocking." But this alone is not enough since the identification of the available capacity is a difficult task. In order for TCP to address these issues, the research community has developed a number of algorithms, such as Additive Increase/ Multiplicative Decrease, Slow Start and Fast Retransmit and Fast Recovery (Peterson and Davie 2003).

In an ad hoc environment the nodes experience higher packet loss rates and longer RTTs. When a route is no longer valid or no longer exists, a route reconfiguration process is called and there is a subsequent delay until the route is established. The sender node is not aware of these events and it confuses the ACK delay or the increase in RTT as a sign of network congestion. This invokes one of the mechanisms mentioned earlier (for example, Slow Start) and the result is unnecessary performance degradation. The above scenario is the reason why TCP needed some improvements and changes to account for the node mobility and the higher packet loss rates. Toh (2002, 224-226) describes some solutions to the problem of TCP over ad hoc and more specifically, TCP-F and TCP-BuS. According to the author "TCP-F is a solution where the TCP source has its timeout values extended and its state preserved when a route is broken. Transmission is subsequently resumed when the route is repaired. TCP-BuS extends this concept further by introducing mechanisms for reliable transmission of feedback control messages, further extending timeout values at each node in the route by avoiding unnecessary fast retransmissions" (Toh 2002, 228).

5. Power Management

The heterogeneity of wireless mesh networks introduces some energy efficiency issues. Parts of these networks can be smaller devices, like PDAs or sensors, which have limited power resources and thus, operational lifetime. Such constraints in the operating hours of a device create the need for power conservation and management. An additional issue in wireless mesh networks is the fact that "each node is acting as both an end system and a router at the same time" (Liu and Chlamtac 2004, 17) and this role can be a real energy drain for smaller devices.

The need to deal with these issues has motivated extensive research into power-aware and power-efficient protocols. Toh (2002, 152) suggests that current algorithms are trying to address the problem in the data link, network and transport layer. Table 1 illustrates the goals of power conservation techniques at the various protocol layers.

Protocol Layer	Power Conservation Techniques
Data-Link layer	Avoid unnecessary retransmissions. Avoid collisions in channel access whenever possible. Put receiver in standby mode whenever possible. Use/allocate contiguous slots for transmission and reception whenever possible. Turn radio off (sleep) when not transmitting or receiving
Network Layer	Consider route relaying load. Consider battery life in route selection. Reduce frequency of sending control message. Optimize size of control headers. Efficient route reconfiguration techniques.
Transport layer	Avoid repeated retransmissions. Handle packet loss in a localized manner. Use power-efficient error control schemes.

Table 1. Power conservation techniques at protocol layer (From Toh 2002, 156)

In addition, power management efforts have emerged in the device (APM, ACPI, etc.) and application levels.

6. Security

Wireless mesh networks are susceptible to security threats since they share open broadcast channels and there is not centralized security control. In other words, the network relies on individual security solutions from each node. Liu and Chlamtac (2004, 17) identify a number of key security issues for ad hoc networking, namely confidentiality, access control, data integrity and DoS attacks. There is extensive research on the security of mesh networks but a further analysis of this topic is beyond the scope of this study.

7. Other Challenges

Mesh networking comes with a number of other challenges. The network's robustness and reliability is crucial in the design and implementation decisions. Furthermore, scalability issues are critical for the successful deployment of large networks. Interoperability concerns raised by the heterogeneous environment are important in building a successful network. Finally, incorporating new technologies, like IEEE standard 802.16 or 802.20, is a constant desire and the mechanisms that achieve this goal should be straightforward.

E. NETWORK LAYER PROTOCOLS

Over the years numerous routing protocols have been proposed to address the network layer challenges in wireless ad hoc networks. Based on the distinct characteristics of these protocols, many authors have described different classes or families of ad hoc protocols that share the same philosophy and have similar features. Belding-Royer (2004) provides a high level view of the most common families and their popular representatives. Halvardsson and Lindberg (2004) give a categorization for the various ad hoc routing protocols and include an extensive research on current approaches. Finally, Wikipedia ("Ad Hoc Protocol List" webpage 2005) includes an extensive list of current implementations and their respective classes. Combining the aforementioned sources, the most common families of ad hoc routing protocols are the following:

- Proactive or table-driven approaches are based on traditional distance vector and link state approaches (Elliott and Heile 2000) used in the wireline Internet. The most popular representatives are OLSR (IETF/RFC 3626 2003), TBRPF (IETF/RFC 3684 2004) and DSDV.
- Reactive or on-demand or source-initiated approaches employ route discovering processes only when a source node needs to send a message to

another node. AODV (IETF/RFC 3561 2003), DSR (IETF Internet Draft and TORA are the most common protocols.

- Hybrid approaches attempt to combine the benefits of the previous two classes. The most common protocol is ZRP.
- Geographical approaches are build on the proactive or reactive family and additionally, incorporate geographical information (for example, GPS position) to support routing. A popular protocol of this category is LAR which is a reactive protocol that uses geographical coordinates to direct routing requests.
- Clustering and hierarchical approaches place nodes into groups based on a number of criteria, commonly location or functionality and try to address scalability issues.
- Multipath routing approaches utilize multiple routing entries per destination in their route tables. Two known approaches are AOMDV and AODV-BR.
- Power-aware approaches have been designed specifically for minimizing energy consumption. GAF and BEE are well known implementations.
- Security-oriented approaches like ARAN and SRP.
- Other approaches that can not be categorized into one of the previous families.

An extensive list of existing protocols and their respective classes is provided in Figure 7.

The focus of our study will be the proactive and reactive classes of ad hoc routing protocols. The reasons for our choice are: (a) this categorization has been adapted by the IETF MANET Working Group and some of the protocols are internet drafts or considered for standardization, (b) it includes the most popular and mature protocols and (c) some of the protocols have already been used in the TNT environment.

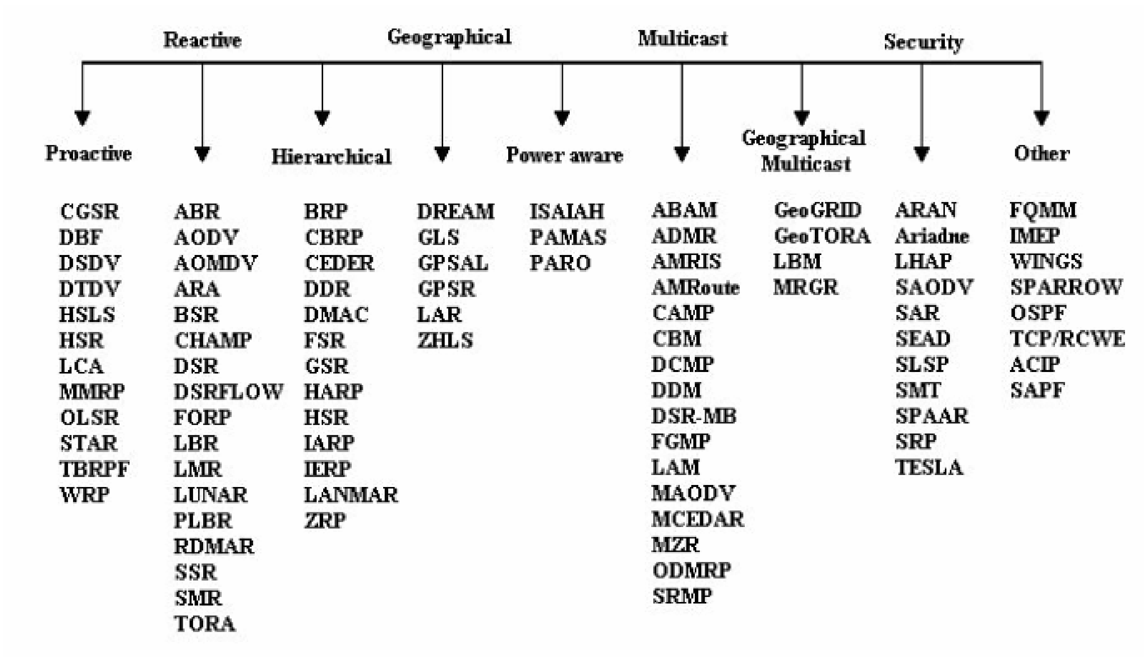


Figure 7. Overview of ad hoc routing protocols (From Halvardsson and Lindberg 2004, 15)

In the proactive family of protocols the route information monitoring is implemented through some combination of periodic and event-triggered message exchange. Topology changes create the need for more control traffic over the network. This is referred to as “background hum” by Elliott and Heile (2000) and represents the main disadvantage of this family. Another disadvantage mentioned by Belding-Royer (2004, 277) is the fact that the routing tables at each node scale at $O(n)$, where n is the number of network nodes. Halvardsson and Lindberg (2004, 12) extend the consequences of control traffic overhead to bandwidth reduction and network congestion. On the other hand, the main advantage of this class is that routes are available the moment needed. The proactive family performs well in networks that employ many data sessions because the control overhead is justified by the high utilization of the paths (Belding-Royer 2004, 277).

The reactive class takes a different road than traditional routing by waiting until the last second to determine the route that the packet will follow through the network. The benefit of this approach is that there is no “background hum” (Elliott and Heile 2000) in the network. However, this approach has a number of drawbacks. The main

disadvantage is the introduction of a “route acquisition latency” (Belding-Royer 2004, 281) which corresponds to the delay required for the discovery of the route. Elliott and Heile (2000) add that the flooding mechanism used for route discovery can be vulnerable to DoS attacks and also, it is difficult to determine when route caches in each node are no longer valid. Reactive approaches perform better than their proactive counterparts in networks with low or moderate traffic loads and high mobility.

In the following paragraphs, a more detailed description of specific protocols from each family is provided. These protocols are used in the next chapter for the design and implementation of wireless mesh nodes.

1. OLSR

The OLSR protocol belongs to the proactive family of ad hoc routing protocols. A complete description of this protocol can be found in other sources (Clausen et al 2001, IETF/RFC 3626 2003). OLSR is based on the traditional link state routing algorithm with few enhancements for ad hoc networks. The key characteristic of this protocol is the use of multipoint relays (MPR) to reduce the overhead of network flooding and link state updates.

The MPR set for a given node consists of a subset of neighboring nodes that covers the whole two-hop neighborhood of this node. When a node broadcasts a message only the nodes belonging to its MPR set rebroadcast this message. The rest neighbors of the node receive the message, but do not rebroadcast it. Nodes learn their two-hop neighbor set by exchanging periodic HELLO messages. Laouti et al (2001) describe the algorithm for calculating the MPR set for each node.

Further, when exchanging link state information, a node mentions only the connections to those neighbors that belong to its MPR set. This information is exchanged through periodic Topology Control (TC) messages. The TC message for a given node contains the set of nodes that have selected the sending node as an MPR. This is described as the MPR Selector set of the node. Only the MPR Selector set is advertised within the network, thus reducing the size of the link state information updates. Once a node receives TC messages from other nodes, it can create routing directions to every node in the network using some sort of shortest path algorithm.

2. DSR

The DSR protocol is a prominent member of the reactive/ on-demand family of ad hoc protocols. Johnson and Maltz (1996) along with the IETF Internet Draft for DSR (2004) provide a detailed analysis of the protocol. The DSR incorporates two main phases: (a) route discovery and (b) route maintenance.

When a node wants to send a packet to another node, it checks its route cache to determine whether it knows a route to the destination. If this route exists and has not expired, then the node uses this information to send the packet. Otherwise, the node tries to discover the destination by broadcasting a route request (RREQ). The nodes that receive the RREQ check whether they know a route to the destination, otherwise they forward the request to other nodes after supplementing it with their own address. By the time the request reaches the destination or an intermediate node that knows how to get to the destination, it contains the necessary addresses that show the sequence of hops taken. In order for the destination node to reply to the source, it must know a route to the source and send a route reply (RREP). In case that the destination node does not know such a route, it can send the RREP along with a RREQ.

Route maintenance is implemented with the use of error packets and acknowledgments. When a node receives a route error, it removes the hop in error from its route cache. Acknowledgements are used to verify that the route links are working correctly.

3. AODV

Another important member of the reactive family is AODV. The behavior and mechanisms employed by this protocol are quite similar with DSR since both protocols are built upon the reactive philosophy. In AODV, route finding is based on a route discovery mechanism that involves broadcasting requests and returning replies with the requested paths. The main tool for maintaining loop-free routes and for having up-to-date routing information is the sequence number of nodes. Moreover, every entry in each node’s routing table is associated with a lifetime value, so when this value expires, the node has to request new routing information.

Belding-Royer (2004, 284) provides some of the differences between DSR and AODV. More specifically, DSR utilizes a route cache that enables multipath routing and route salvaging. In DSR, the route entries are not required to have a lifetime value. Also at the MAC layer, DSR provides the option of promiscuous listening which enables various nodes to receive data that are not addressed to them.

A complete description of AODV is provided by Perkins and Royer (2000). Also, a very detailed analysis of AODV's mechanisms can be found in IETF RFC 3561 (2003).

F. COMPARATIVE STUDIES OF ROUTING PROTOCOLS

The ad hoc routing protocols have received significant attention by the academic community since they face important challenges and, at the same time, try to address hard problems. There are many published studies on performance comparisons of different protocols in a variety of scenarios. In this section we are going to highlight some of the most important studies and analyze their conclusions.

Broch et al (1998) used the ns-2 simulator to compare four protocols, DSDV (proactive), TORA, DSR and AODV (reactive). The metrics used was packet delivery ratio, routing overhead and path optimality. The simulation results showed that all of the protocols delivered a greater percentage of the originated data packets when there was little node mobility. Also, DSR and AODV performed particular well regardless of the mobility rate. Finally, DSR exhibited the least overhead while TORA created the most. Das et al (1998) analyzed the performance of the same protocols using a discrete event, packet-level, routing simulator called MaRS (Maryland Routing Simulator). Their scenarios involved 30 and 60 node mobile networks and the chosen metrics were fraction of packets delivered, end-to-end delay and routing load. The authors concluded that their results are very similar with the work of Broch et al (1998). Johansson et al (1999) focused on a simulation analysis of DSDV, DSR and AODV. They used the ns-2 simulator as their simulation environment and their conclusions are also similar to the previous studies.

Royer and Toh (1999) provided a comparison of table-driven approaches (DSDV, CGSR and WRP) and source-imitated protocols (AODV, DSR, TORA, ABR and SSR). Their conclusion regarding the communication complexity of the first family of protocols

is “since DSDV, CGSR and WRP use distance vector shortest-path routing as the underlying routing protocol, they all have the same degree of complexity during link failures and additions” (Royer and Toh 1999, 53). This is not true for the second category of protocols. The overall comparison of the two families illustrate the advantages and disadvantages described in previous sections and add that in reactive approaches signaling traffic grows with increasing mobility of active routes while in proactive protocols the signaling traffic is always greater. Lee et al (1999) used the GloMoSim software to simulate a network of 30 mobile nodes using DBF (proactive), DSR and ABR (reactive). The metrics used were control overhead, data throughput and end-to-end packet propagation delay. The results showed that (a) both ABR and DSR on-demand routing schemes had considerably less overhead than DBF, (b) ABR demonstrated higher throughput and smaller delays than the others and (c) ABR exhibited a higher storage overhead than DSR.

A comparative study of DSR and AODV using the ns-2 simulator was provided by Das et al (2000). Their performance metrics were packet delivery fraction, average end-to-end delay and normalized routing load. The authors observed that DSR exhibited a lower routing load than AODV but performed worst regarding the delivery fraction and delay. Dyer and Boppana (2001) also used the ns-2 simulator to compare the TCP performances of two on-demand algorithms, AODV and DSR, and a proactive algorithm, ADV. Bansal and Barua (2002) studied the DSR and AODV protocols using the ns-2 tool. The main conclusions of their study were that (a) AODV performed better than DSR under high mobility, (b) DSR performance was better in low mobility environment, (c) AODV had a higher routing overhead while DSR’ overhead increased with mobility and (d) DSR performed better that AODV when connection density was high.

Sholander et al (2002) provided an experimental comparison of OLSR and WARP. The first protocol is part of the proactive class while the second is hybrid and is based on ZRP with additional enhancements for QoS support. The authors concluded that WARP had lower packet loss fractions and for one case, WARP’s lower packet loss produced 50% more overhead for the lowest mobility rate. Bhandare et al (2003) used a hardware test-bed to compare certain aspects of DSR and EADSR. The test-bed consisted of laptops equipped with Cisco Aironet 350 series wireless Ethernet cards and each node

included a packet protocol development environment (based on Click) running on Linux Red Hat 7.2. The authors concluded that “DSR transmits packets at full power using minimum hop routes. This makes the implementation energy-inefficient... the EADSR protocol is more power efficient as compared to DSR” (Bhandare et al 2003, 1173).

Gray et al (2004) performed an indoor and outdoor comparison of APRL, AODV, ODMRP and STARA, running on top of thirty-three 802.11-enabled laptops moving randomly through an athletic field. APRL and STARA belong to the proactive class of protocols while AODV and ODMRP to the reactive family. Their conclusion was that, in general, reactive algorithms performed better for the selected number of nodes and traffic load. Also, ODMRP was better than AODV although its performance degraded indoors due to different levels of contention. Finally, Boukerche (2004) studied and compared the performance of AODV, PAODV, CBRP, DSR, and DSDV using the ns-2 simulator. The first four are on-demand protocols and the last one is table-driven. The simulation design involved 50 and 100 nodes with a combination of 10, 20 and 30 connections while the selected metrics were throughput, average end-to-end delay and normalized routing overhead. The author reported that in the various scenarios there was no absolute winner since each protocol outperformed the others in some metrics, while it was inferior in other cases. His final conclusions included: (a) the two source routing based protocols, DSR and CBRP, had very high throughput while the distance-vector based protocol, AODV, exhibited a very short end-to-end delay of data packets, (b) CBRP had a higher routing overhead than DSR, (c) DSR had much smaller routing overhead than AODV and CBRP, (d) AODV had the largest overhead among the three protocols and (e) PAODV outperformed slightly the original AODV (Boukerche 2004, 341).

The important observation from the above studies is that the performance of various routing protocols is heavily influenced by the particular scenarios they are employed. Characteristics such as number of mobile nodes in the network, mobility rate, traffic load, number of data sessions and more can prove crucial in the protocol performance. As Belding-Royer (2004) observed, “it is likely that there does not exist a single routing protocol that can solve the needs of every conceivable ad hoc network scenario. Rather, the selection of a routing protocol for a given network is likely to be dependent upon the dominating characteristics of this network.” Regarding the

comparison of families of ad hoc protocols, Elliott and Heile (2000) also concluded that "it is unlikely that one family of routing protocols is in every case superior to the other." In the next chapters, we will use the above observations to compare different families of routing protocols based on the specific needs of the network that are used.

III. TOOLKIT IMPLEMENTATION

A. INITIAL DESIGN CONSIDERATIONS

There are a number of important factors that influence the design and implementation decisions for the wireless mesh toolkit. One of the critical design considerations is the selection of the appropriate mesh routing protocols. As it was mentioned earlier in Chapter 2, we decided to focus on the proactive and reactive families of protocols since this categorization is adapted by the IETF MANET Working Group, it includes the most popular and mature protocols and finally, some of these protocols have already been used in TNT experiments. Based on this observation, we selected the following protocols from each family:

- The OLSR protocol from the proactive class. The choice of OLSR was influenced by the fact that it is in the focus of the IETF MANET Working Group (RFC 3626 2003) and it has been used in the TNT environment as the main routing protocol for the mesh clusters.
- The DSR protocol from the reactive/ on-demand family. This protocol is standardized by the IETF MANET Working Group and is considered quite matured.
- The AODV protocol from the reactive/ on-demand class. The IETF MANET Working Group has shown interest in this implementation (RFC 3561 2003) which is considered quite stable and promising.

Another important consideration is the modeling environment. There are many tools available that can be used to model and analyze the wireless mesh toolkit. The decision to choose among them was based on usability and extensibility factors. This issue will be further analyzed later on in this chapter.

Finally, in the design phase we are also concerned about the types of nodes to include in the wireless mesh toolkit. Based on the TNT environment, we decided to model the following nodes:

- Laptops
- Sensors

Each one of these nodes exhibits distinguished characteristics that should be reflected by the toolkit. The modeling considerations for each node will be addressed in subsequent sections.

Overall, we have identified three important areas of concern that should be addressed before moving to the implementation phase. These include the appropriate choice of routing protocols, simulation environment and types of nodes.

B. MODELLING ENVIRONMENT

There are several network simulators that have been used both by academia and industry communities. Each one demonstrates strengths and weaknesses in particular areas, so the decision to use one of them should take into account the scope and purpose of the mesh toolkit.

1. Simulation Programs

Boukerche and Boloni (2004) list a number of simulation programs for wireless and mobile networks. Also, Halvardsson and Lindberg (2004) provide their insights into different simulation environments. According to these sources, OPNET (OPNET Training 2004) is a professional environment for the modeling, simulation and performance analysis of wireless and wired networks. Its two distinct features include the sequential discrete event simulation capability and the hierarchical modeling structure, meaning the decomposition of the model into different levels of detail. The main disadvantages of OPNET are scalability, learning curve and cost (Boukerche and Boloni 2004, 395). The simulation tool does not scale well, it exhibits a steep learning curve and it is a commercial product that requires a certain cost for maintaining a working license.

GloMoSim (Global Mobile Information System Simulator) is developed at UCLA Parallel Computing Laboratory (UCLA PCL) and is intended for academic use only. This tool supports parallel and sequential simulation analysis of wireless and wired networks. It has been developed using PARSEC (Parallel Simulation Environment for Complex Systems) which is a C-based simulation language that “adopts a message-based approach to discrete event simulation” (Boukerche and Boloni 2004). GloMoSim supports a number of ad hoc routing protocols, namely AODV, DSR, Fisheye, LAR, ODMRP and WRP. The main difficulty of this environment is that the creation of new protocols requires familiarity with PARSEC and the corresponding compiler. Another simulation environment is QualNet which is a commercial product derived from GloMoSim with the addition of some extensions. The tool was developed by SNT (Scalable Network Technologies) and supports a MANET library which includes models for providing

wireless dynamic routing, mobility, and other. This library supports the following routing protocols: DSR, Fisheye, LANMAR, LAR, OLSR, STAR, ZRP, IERP, IARP, BRP and ODMRP (multicasting). The main disadvantage of this environment is that it is a commercial product requiring license maintenance operations.

The network simulator ns-2 is another tool that supports discrete event simulations for wired and wireless networks. According to Boukerche and Boloni (2004, 396), the ns-2 has evolved from the REAL network simulator and now includes important wireless additions from the UCB Daedelus and CMU Monarch projects and Sun Microsystems. The actual software is open-source and it is maintained by ISI, the Information Sciences Institute at the USC School of Engineering. The most recent version of ns-2 is ns-2.28 released February 3rd, 2005 and this supports AODV, DSDV, DSR, TORA, MAODV, ODMRP, ZRP and other routing protocols. Although ns-2 is probably the most popular network simulation tool, it is part of an ongoing research effort and this has a serious impact on program stability, bug issues and provided support.

Like ns-2, OMNeT++ is a freely-distributed discrete event simulator written in C++. According to OMNET++ homepage ("OMNeT++ Community Site" webpage 2005), it "provides a component architecture for models. Components (modules) are programmed in C++, then assembled into larger components and models using a high-level language (NED)." This tool provides minimal support for ad hoc routing protocols.

Boukerche and Boloni (2004) describe some other environments, namely INSANE, NetSim, and SWiMNET. INSANE is mostly focused on ATM network simulations, while NetSim is suitable for Ethernet analysis. The last one, SWIMNeT, was developed by Boukerche et al (2001) as a high performance simulator for mobile and wireless networks. Unfortunately, this tool was not publicly available, so there is not sufficient information to evaluate its contribution. Other less known tools are described by NIST in their WCTG site ("Ad Hoc Wireless Networking Links" webpage 2005).

2. Our Choice

Although ns-2 was the most desirable candidate due to its popularity and open-source nature, we selected OPNET Modeler 10.5.A for the following reasons:

- NPS currently maintains an educational license for this tool which is installed in the GigaLab.

- OPNET Techologies Inc. provides extensive support, documentation and training material for their products.
- It is a professional tool characterized by stability, helpful features, adjustable simulation parameters and various presentation graphs. All these elements are essential in our study.
- There are known implementation of the OLSR, DSR and AODV protocols in this environment.

The dominant characteristic of this environment is the model decomposition to several layers of detail (Figure 8). The higher level representation corresponds to the network model which is a collection of individual nodes. Each node is described by a node model in which one or more modules are connected by packet streams or statistic wires. Every node module contains process models. A process model is represented by a state transition diagram (STD) that describes the behavior of a node module in terms of states and transitions. The process model is basically a finite state machine (FSM) which defines the states of the module and the criteria for changing the states. FSMs use states and transitions to determine what actions the module can take in response to an event. Operations performed in a state are described in C/ C++ code. OPNET allows the user to attach fragments of C/ C++ code to each part of the FSM. This code, augmented by OPNET-specific functions, is called Proto-C. According to OPNET's documentation, Proto-C is mainly used in the following areas:

- Enter Executive (Enter Execs) which is code executed when the module moves into a state.
- Exit Executive (Exit Execs) which is code executed when the module leaves a state.
- Transition Executive which is code executed in response to a specific event.

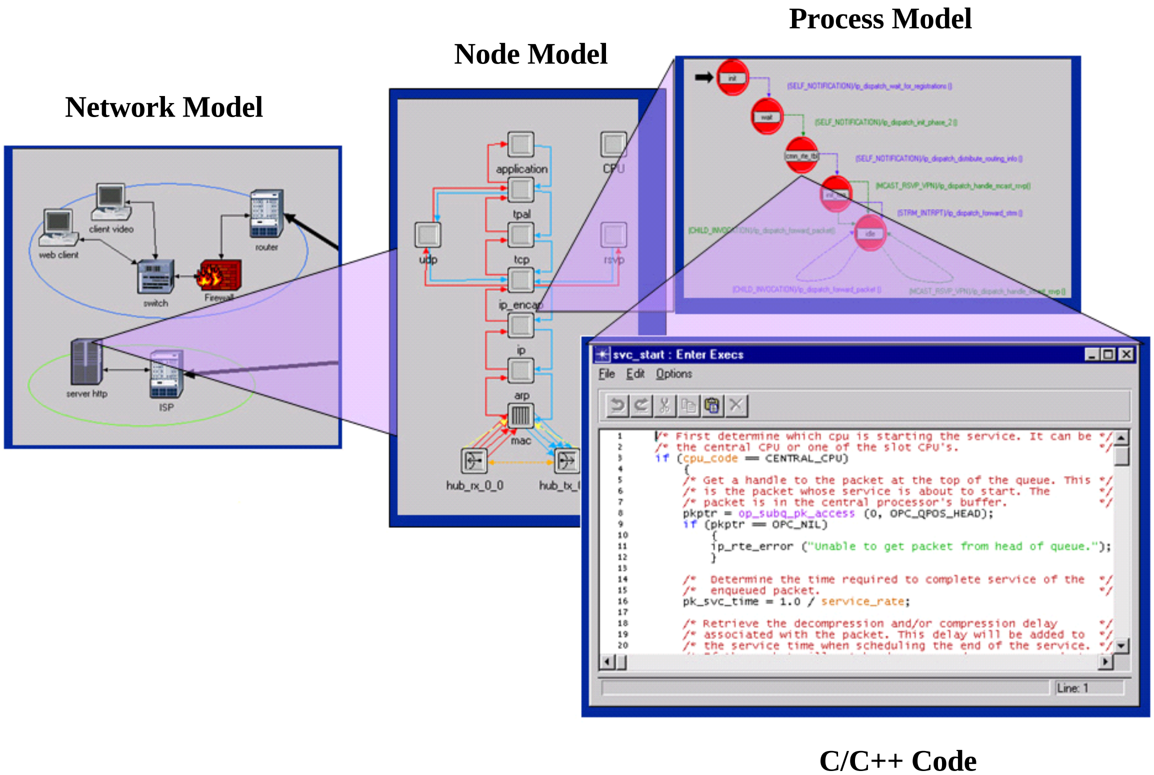


Figure 8. OPNET model decomposition (After OPNET Training 2004, 4)

C. TOOLBAR CREATION

The first step in creating the wireless mesh toolkit involves the implementation of an empty OPNET toolbar. Eventually this toolbar will display the nodes that we are going to create later on in this chapter.

Before creating the actual toolbar, we need a folder that will contain this toolbar and all of the node models. The name of this folder is TNT_Toolkit. Each OPNET toolbar is described by a .cml file, so we name ours as @TNT_Toolkit.cml. In order to load the toolbar each time the environment boots, we should include the folder path in the mod_dirs parameter of OPNET.

The first items that need to be inserted in the toolbar are the various configuration utilities of OPNET, namely “Application Config”, “Profile Config”, “Task Config”, “Mobility Config” and “RXgroup Config”. The application configuration node is used to globally define application traffic in the network, while the profile configuration object defines a reusable collection of applications that describe the activity patterns of an

individual user or a group of users. The applications defined in the “Application Config” object are used by the “Profile Config” object to configure profiles. The “Task Config” node can be used to define or create tasks that characterize custom applications. These applications are then used to create profiles, which can be applied across different nodes to generate desired traffic. The mobility object is used to define mobility profiles for individual nodes. Finally, the “Rxgroup Config” node is useful in limiting the set of possible receivers that a node can communication with.

Furthermore, OPNET 10.5.A already includes a number of MANET nodes that are useful for the toolkit. These nodes are the “manet_station”, “wlan_wkstn”, “wlan_server”, “wlan_ethernet_router” and “wlan2_router”. The MANET station represents a raw packet generator transmitting packets over IP and WLAN, while the WLAN workstation is a classic workstation that supports client-server applications. The WLAN server is the model of a server node that supports one underlying IEEE 802.11 interface. Finally, the difference between the two router nodes is that the WLAN Ethernet router provides one Ethernet and one IEEE 802.11 interface while the other one has only two wireless interfaces.

Up to this point, the toolkit has incorporated utilities and nodes provided by OPNET. The contents of the toolbar file (@TNT_Toolkit.cml) are illustrated in Figure 9, while the representation of the actual toolbar inside the modeling environment is shown in Figure 10. In the next paragraphs we are going to enhance the functionality of the toolkit by inserting more nodes in the OPNET toolbar.

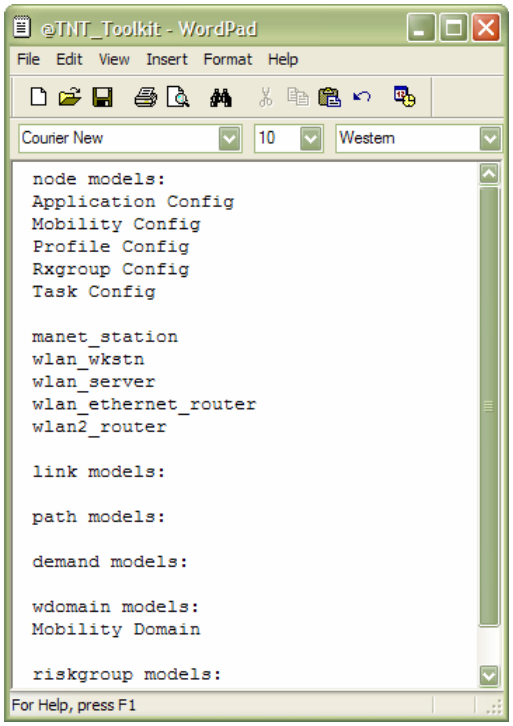


Figure 9. Toolbar file

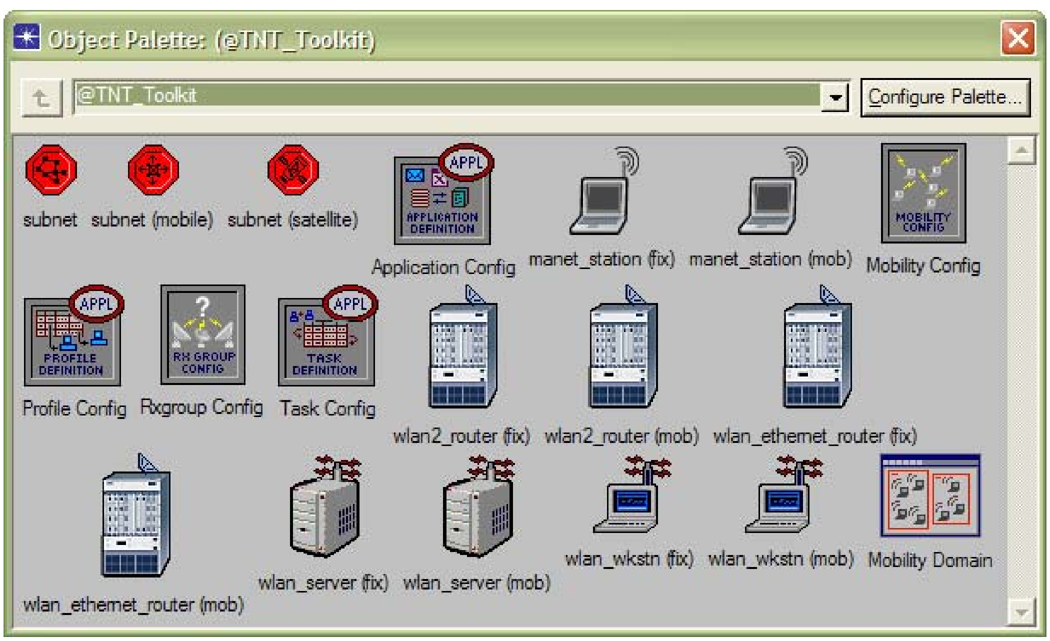


Figure 10. Toolbar contents

D. LAPTOP MOBILE AND FIXED NODES

The laptop model represents the majority of nodes that exist in a mesh environment. Its main characteristics include wireless communication through IEEE 802.11 interfaces, mobility and sufficient processing power, storage capability and batter capacity. The actual model is derived by known OPNET implementations of the corresponding protocols. The only necessary addition is to create models that support both mobile and fixed nodes.

Furthermore, we derived PDA nodes from their corresponding laptop implementations. The PDA nodes represent devices that have similar characteristics with laptops. Their main difference has to do with lower processing power, smaller storage capability and most importantly, battery capacity. The modeling process in OPNET uses a high level abstraction of the actual device, thus it is very difficult to account for these differences. Our approach was focused only in the presentation layer, meaning that the behavior of laptop and PDA models is the same and their only difference is the way they are represented in OPNET. The reason for this addition is that it is more user-friendly and also, more intuitive for the modeling team to use a PDA abstraction for a PDA device. In the derivation process we chose to use only mobile PDA nodes, since this is dictated by the nature of this device.

1. OLSR

For the implementation of OLSR capable laptops we used the simulation code that is provided as part of the QOLSR project of the LRI (Laboratoire de Recherche en Informatique) of Universiti de Paris Sud in France. The protocol model is available from the LRI website (“Project QOLSR Simulations” webpage 2005). This code is provided as a package of files that demonstrate the OLSR behavior and characteristics. Before we started to work with the model, we identified and removed a number of files that were not necessary for our study. These files are listed in the Appendix.

The next step involved the derivation of a laptop node from the corresponding OLSR protocol node. This was achieved by using the MANET_OLSR_PROTOCOL_ _NODE_MODEL.nd.m file to derive the olsr_node_laptop.nd.d file (Figure 11). Our model inherited all the attributes of the OLSR protocol and moreover, it supported two types of nodes, namely mobile and fixed. Finally, we tested the proper functionality of

our model in two ways: (a) by compiling the code of each node module and (b) by running a number of simulations. The node modules were compiled successfully and a simulation scenario of 20 OLSR nodes was completed without any problems.

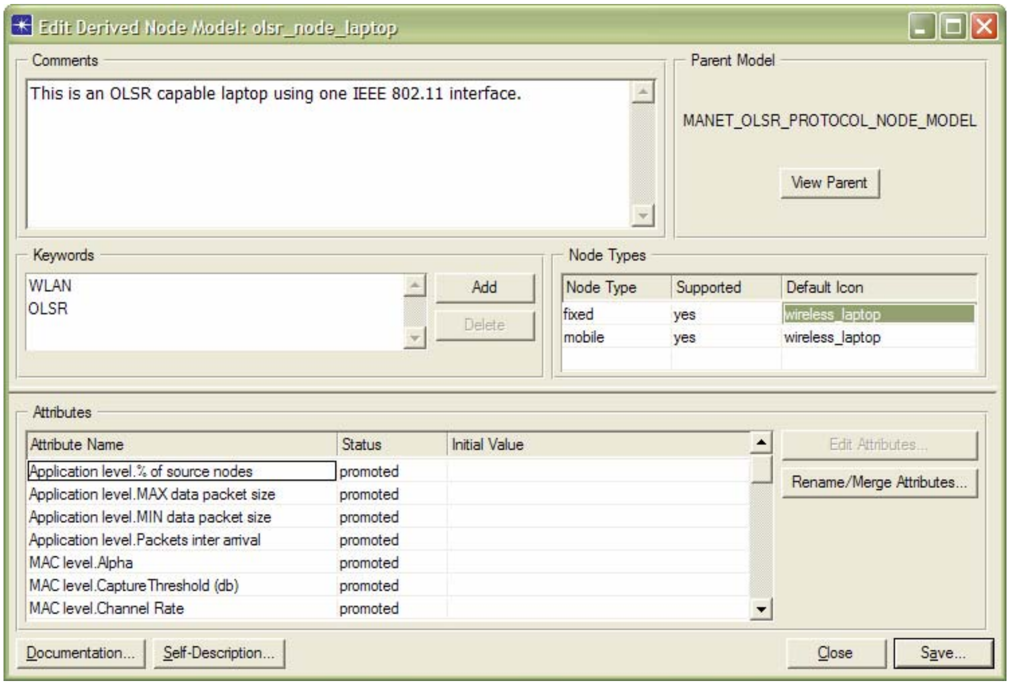


Figure 11. OLSR laptop node derivation

The OLSR PDA node was derived by the corresponding OLSR laptop node that was created earlier. This was achieved by using the olsr_node_laptop.nd.d file to derive the olsr_node_pda.nd.d file (Figure 12). The model inherited all the attributes of the OLSR protocol and moreover, we chose to support only mobile nodes.

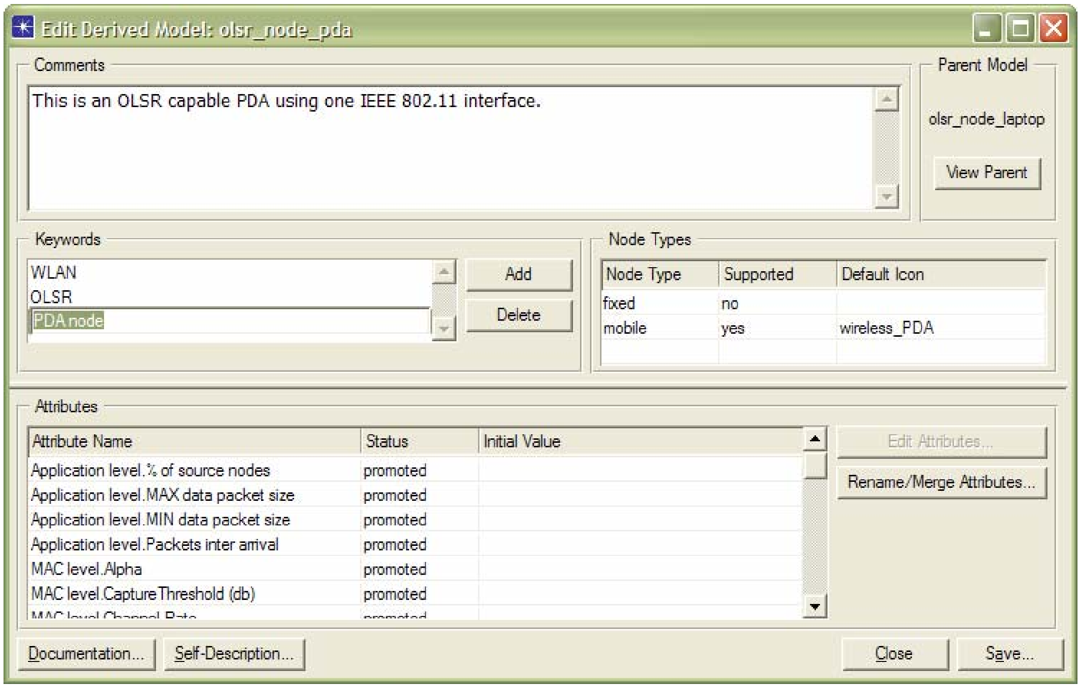


Figure 12. OLSR PDA node derivation

2. DSR

The DSR laptop implementation was based on the AFIT DSR model created by Ballah (2002). This model is available through NIST ("DSR model" webpage 2005). Similar to the previous protocol, the code is provided as a package of files that demonstrate the DSR behavior and characteristics. The files that were unnecessary for our purpose and were removed from the AFIT DSR model package are listed in the Appendix.

The implementation phase involved the derivation of a laptop node from the corresponding DSR protocol node. This was achieved by using the dsr_node.nd.m file to derive the dsr_node_laptop.nd.d file (Figure 13). Our model inherited all the attributes of the DSR protocol and moreover, it supported two types of nodes, namely mobile and fixed. Finally, we tested the proper functionality of our model in two ways: (a) by compiling the code of each node module and (b) by running a number of simulations. The node modules were compiled successfully and a simulation scenario of 10 DSR nodes was completed without any problems.

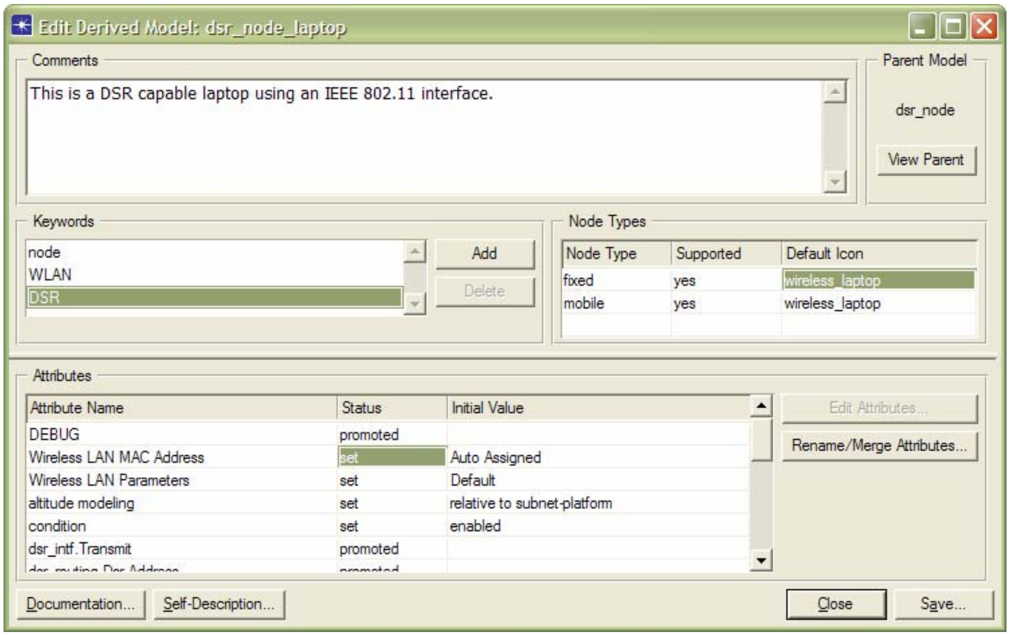


Figure 13. DSR laptop node derivation

The DSR PDA node was derived by the corresponding DSR laptop node. This was achieved by using the dsr_node_laptop.nd.d file to derive the dsr_node_pda.nd.d file (Figure 14). The model inherited all the attributes of the DSR protocol and moreover, we chose to support only mobile nodes.

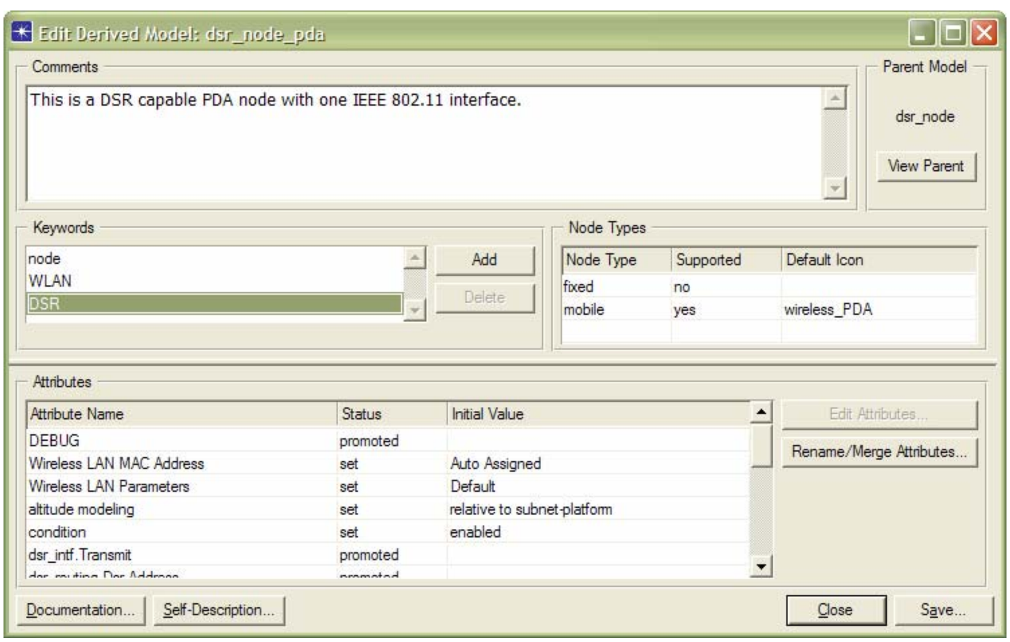


Figure 14. DSR PDA node derivation

3. AODV

The creation of the AODV capable laptop was based on the NIST AODV model which is available from NIST ("AODV model" webpage 2005). The protocol package included a number of files that were unnecessary for this research. A list of the files we removed can be found in the Appendix.

The implementation phase involved the derivation of a laptop node from the corresponding AODV protocol node. This was achieved by using the aodv_node.nd.m file to derive the aodv_node_laptop.nd.d file (Figure 15). Our model inherited all the attributes of the AODV protocol and moreover, it supported two types of nodes, namely mobile and fixed. Finally, we tested the proper functionality of our model in two ways: (a) by compiling the code of each node module and (b) by running a number of simulations. The compilation of the code revealed a number of errors because this model was created for OPNET version 7. We debugged the code and succeeded in making it work for a simulation scenario of 20 nodes.

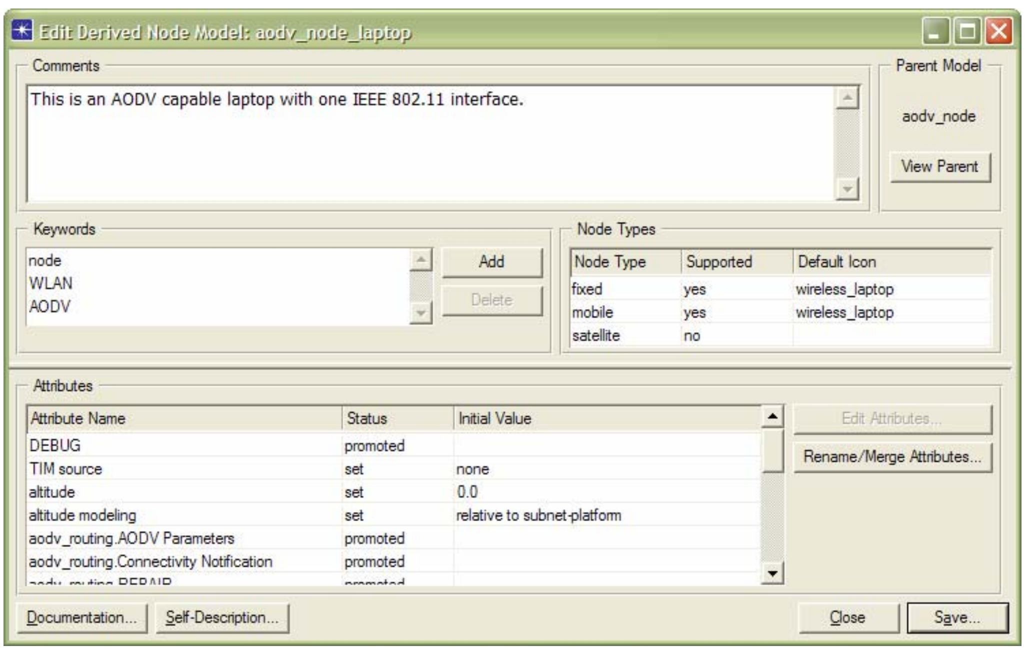


Figure 15. AODV laptop node derivation

The AODV PDA node was derived by the corresponding AODV laptop node. This was achieved by using the aodv_node_laptop.nd.d file to derive the

aodv_node_pda.nd.d file (Figure 16). The model inherited all the attributes of the AODV protocol and moreover, we chose to support only mobile nodes.

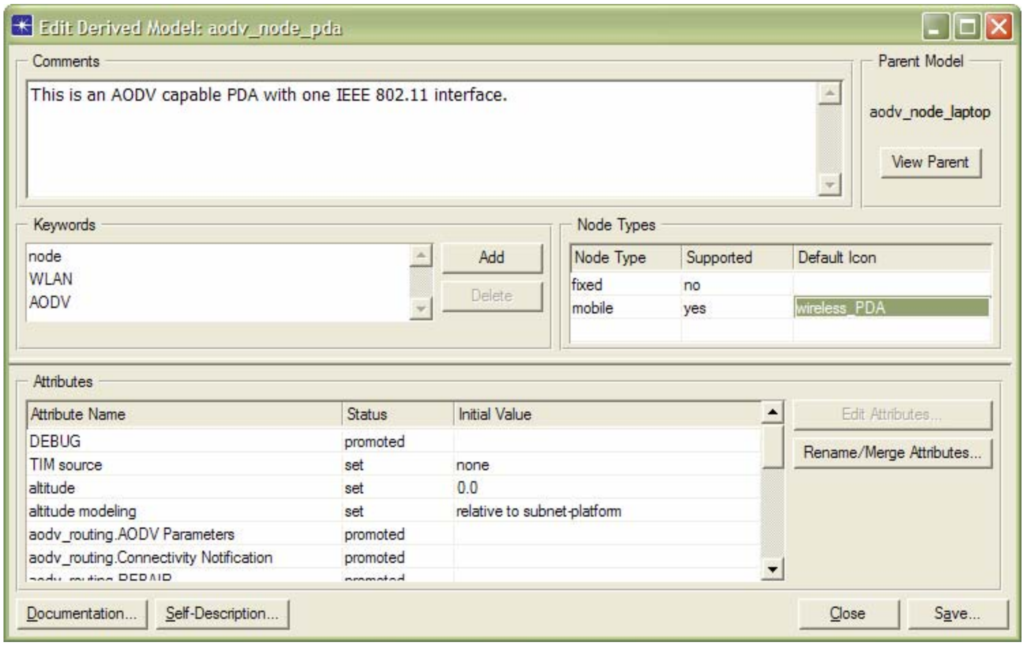


Figure 16. AODV PDA node derivation

E. SENSOR NODES

The sensor nodes represent stationary, low power devices that are connected to the mesh cluster and provide information on various activities, such as temperature, movement, and others. Past TNT experiments have used wired stationary sensors connected to fixed laptops. The connectivity to the mesh cluster was achieved through the laptops. This approach deviates from the concept of wireless ad hoc sensor networks introduced in the literature. Hac (2003) illustrates that these networks demonstrate some sort of intelligence (smart sensor networks), they are power-aware (distributed power-aware microsensor networks) and they involve routing features. More specifically, “sensor networks are dense wireless networks of heterogeneous nodes collecting and disseminating environmental data.... Self-configuring wireless sensor networks consist of hundreds or thousands of small, cheap, battery-driven, spread-out nodes...” (Hac 2003, 101). Also, NIST(“Wireless Ad Hoc Networks: Smart Sensor Networks” webpage 2005) identifies a number of challenges for these networks like support for large number of sensors, low energy consumption and efficient routing.

Our approach was based on the TNT profile, so the sensor model will not exhibit wireless connectivity, mobility and routing capabilities. These features will be provided by the laptop node connected to the sensor. The model of the sensor nodes was derived from the basic Ethernet client. This was achieved by using the ehternet_wkstn_adv.nd.m file to derive the sensor_node.nd.d file (Figure 17).

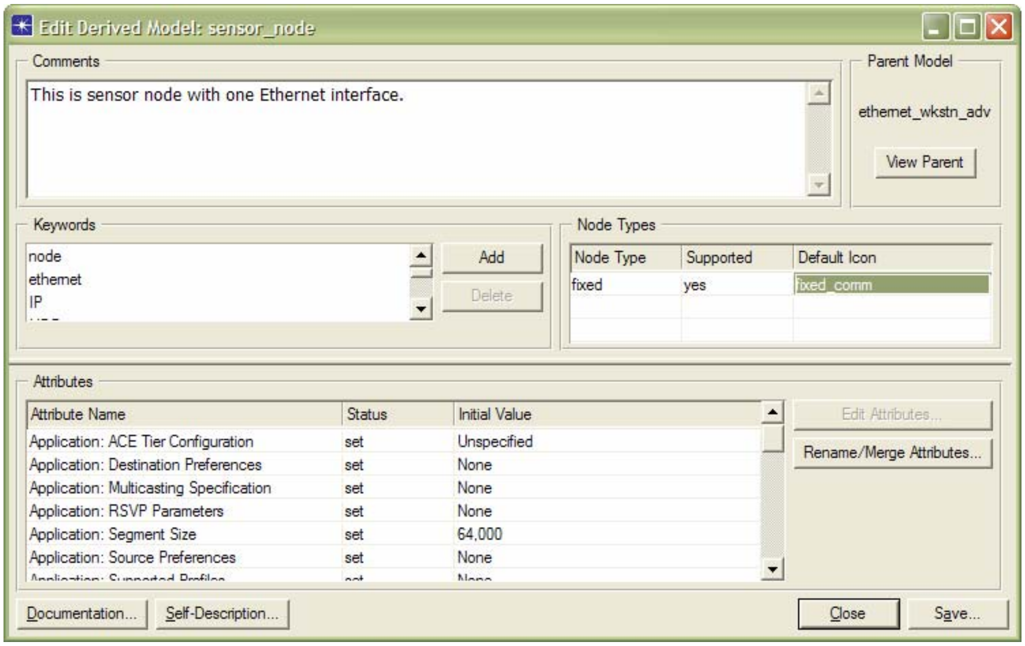


Figure 17. Sensor node derivation

The derived sensor node is fixed and can be connected to the mesh cluster by using the fixed wlan_ethernet_router which already exists in our toolbar. The two nodes can be connected with a 10BaseT, 100BaseT, 1000BaseX or 10Gbps Ethernet link. The last four links are inserted as link models in the TNT toolkit. An example of sensor connectivity to the mesh cluster is shown in Figure 18.

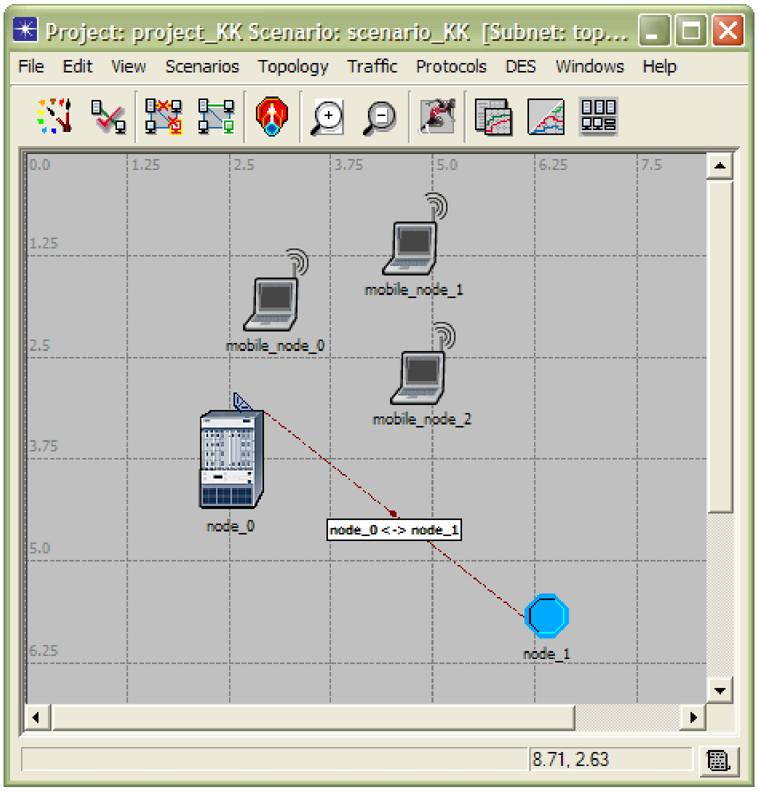


Figure 18. Example scenario of sensor connectivity to mesh cluster

F. CONCLUSION

During the design phase of the modeling task we identified a number of issues that should be resolved in order to implement a correct model. These issues included the selection of ad hoc routing protocols, modeling environment and types of nodes. An appropriate model design should address all of the above concerns. We decided to model OLSR, DSR and AODV protocols because they are standardized by the IETF MANET Working Group, they are mature and some of them have already been used in TNT experiments. For the modeling environment we selected OPNET mainly because it is licensed by the IS department's GigaLab. Finally, we decided to model two types of network nodes, namely laptops and sensors.

In order to succeed in the modeling task of nodes, we had to consider and provide support for the distinct characteristics of each type of node. For laptop nodes these characteristics included wireless communications, sufficient processing power and battery life, adequate storage capability, mobility and support for fixed and mobile nodes.

The modeling of sensors was influenced by past TNT experiments. Their main characteristics included wired, fixed nodes attached to a laptop that provided connectivity to the mesh cluster.

Based on the above observations, we implemented a mesh network toolkit for OPNET. The first additions to the toolkit were current OPNET configuration utilities and MANET files. After that, we implemented a number of nodes supporting the selected protocols. The final contents of the toolkit file (@TNT_Toolkit.cml) are illustrated in Figure 19, while the representation of the complete toolbar inside the modeling environment is shown in Figure 20.

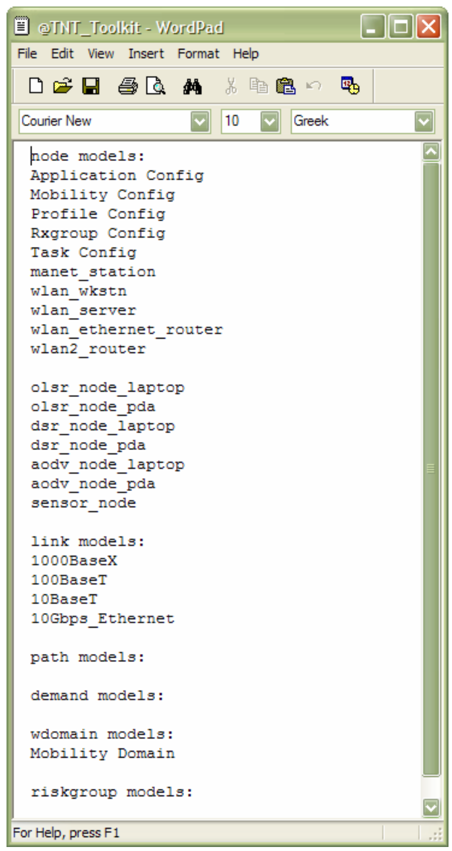


Figure 19. Final version of toolbar file

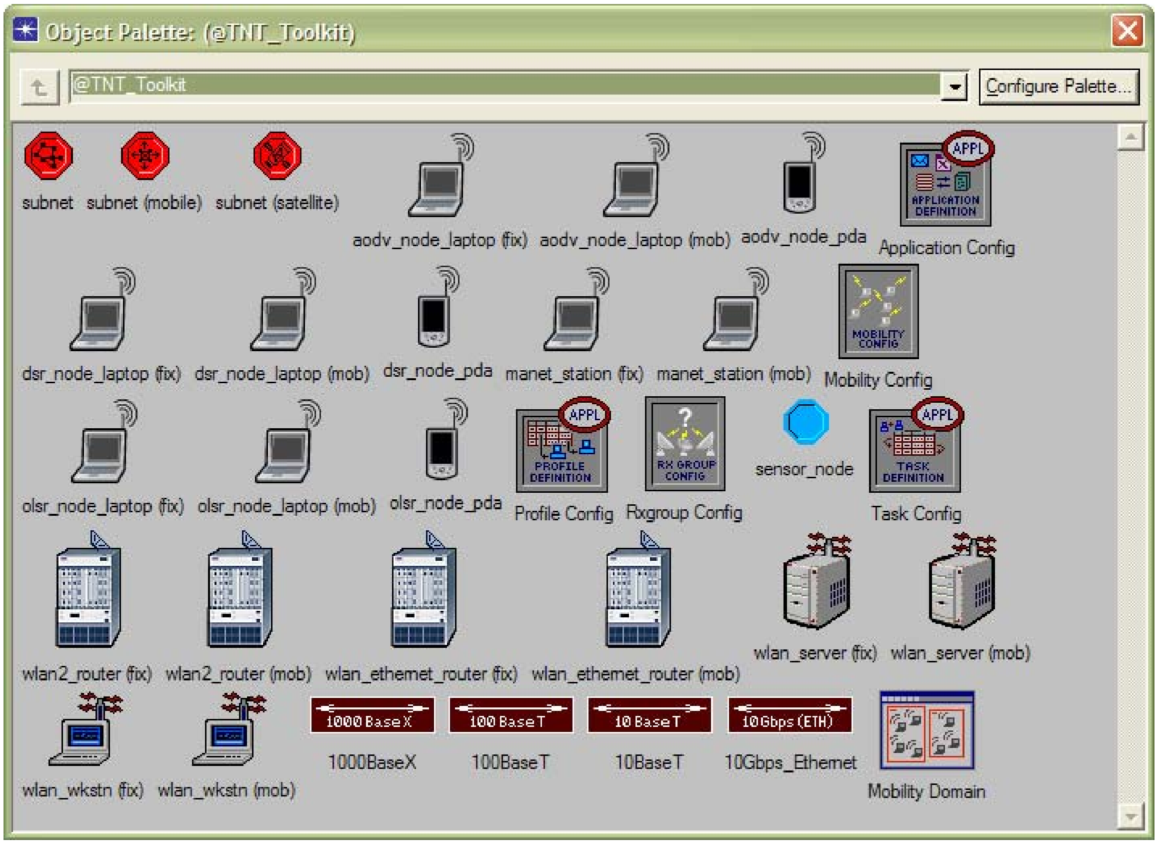


Figure 20. Final version of toolbar contents

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IV. SIMULATION ANALYSIS

A. TOOLKIT USAGE

The wireless mesh toolkit was created to support the TNT program. The desirable characteristics of this toolkit are the ability to incorporate new routing protocols, to support new types of nodes and to complement experimental scenarios. The process of adding new protocols and nodes is quite simple and can follow the steps used in the previous chapter. Furthermore, the toolbar can support various TNT scenarios by providing the nodes that can model network configurations. The simulation of these network models can reveal performance bottlenecks and potential problems. All this information is valuable to the experimental team since the time and cost to design and execute the actual experiments is far greater than simulation runs. Moreover, a simulation environment can be a more efficient way to address scalability issues. Building a mesh cluster with 100 nodes and making sure that it works according to the design is easier in a professional simulation environment than in real life. Overall, the toolkit's extensibility and usability can be considered beneficial for the TNT project.

B. THE TNT PROJECT

The TNT program is a joined field experimentation effort that is supported by many NPS academic departments, DoD and USN participants and independent contractors. The formal objective of the project is to conduct a series of quarterly studies and experiments in order to develop a network that can support and enhance the warfighting capabilities of the Special Operation Forces (SOF).The program's research areas span in many diverse directions, such as mesh topology, IEEE 802.16 as network backbone, IEEE 802.16 OFDM, propagating UAV control over mesh clusters and SATCOM, network vulnerability and security, collaborative technologies and many more. The focus of this study is the modeling and simulation of mesh clusters.

In order to effectively research the mesh modeling and simulation issues, it is not sufficient to study the mesh clusters in isolation. It is important to identify the context in which mesh clusters are deployed in the experiments and model the specific details. The main philosophy of the TNT mesh topology is to eliminate the IEEE 802.11 range limitations by using IEEE 802.16a as the network backbone. The standard Wi-Fi

interfaces can be used inside the local mesh clusters but for connectivity in longer distances we have to take advantage of the emerging IEEE standard 802.16. This idea is illustrated in Figure 21.

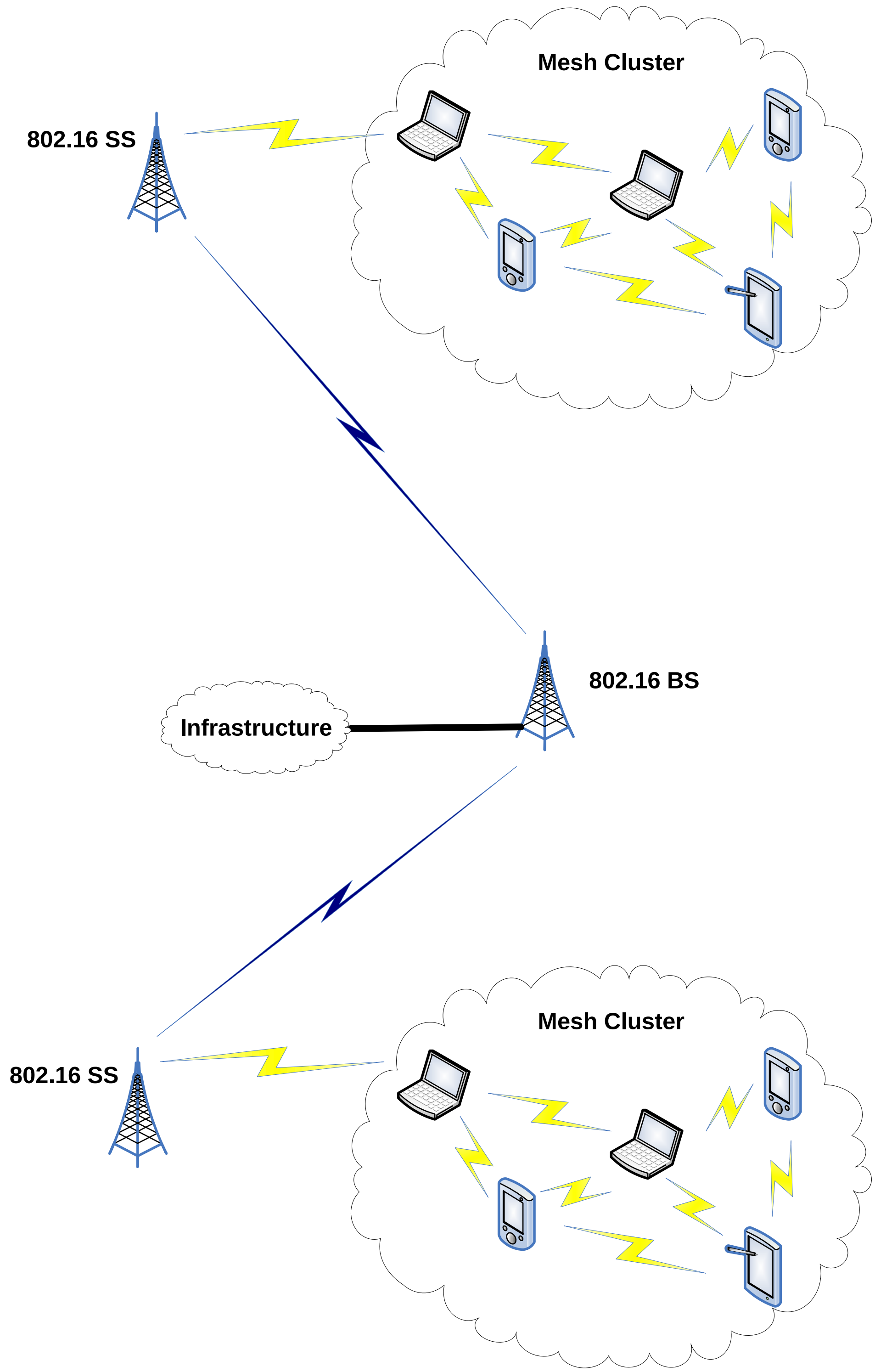

Figure 21. TNT mesh topology and IEEE 802.16

In this context and in order to study the effects of mesh routing protocols on the network, it is important to consider the IEEE 802.16 backbone. A high level overview of this standard along with a model approximation is provided in the next paragraph.

C. IEEE 802.16 AND DOCSIS

The basic building blocks of the IEEE 802.16 architecture (Figure 22) are the base station (BS) and the subscriber stations (SS). The BS is equipped with a sectorized antenna that can serve simultaneously multiple areas and is typically located on a building that is connected to the public network. The BS transmits at a given frequency in each sector so all the subscriber stations are able to receive the same information. Each SS share the uplink to the BS on a demand basis.

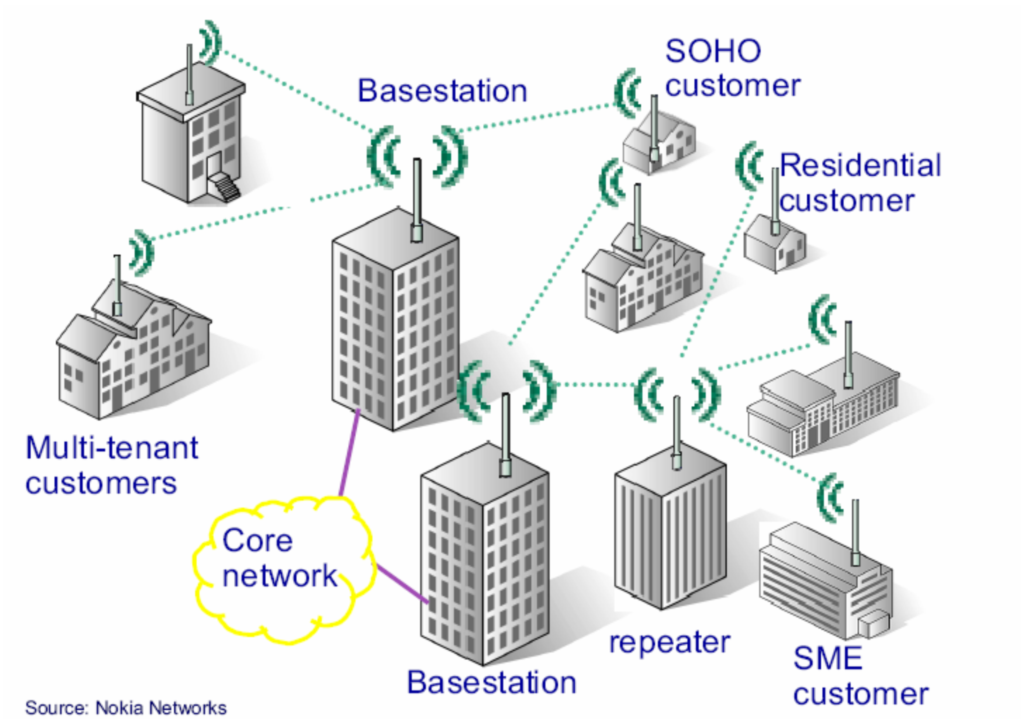

Figure 22. IEEE 802.16 architecture (From IEEE C802.16-02/09 2002, 7)

The IEEE standard 802.16 is applicable to frequencies between 10 and 66 GHz, while the IEEE 802.16a covers frequencies between 2-11 GHz. The main features of the IEEE 802.16 PHY are long range operations (up to 30 miles), NLOS performance and 124 Mbps maximum throughput per channel (70 Mbps/channel for IEEE 802.16a). More details for the PHY specification and the supported schemes for each case can be found

in the IEEE standard 802.16 (2004, 307). Further, the IEEE 802.16 MAC introduces some new concepts especially in contention resolution and connection establishment between BS and SS. The main mechanism for dealing with these two issues is related to a message flow process between the BS and SS that guarantees connection setup and collision avoidance (IEEE Std 802.16-2004). Overall, it is obvious from the above high level description of IEEE 802.16 that this type of wireless interface can be effectively used for the role of network backbone.

1. DOCSIS Concept

At present, there is no known implementation of IEEE 802.16 in OPNET. Since we need this model for the analysis of the mesh clusters' performance, we have to accept the model approximation proposed by Ramachandran et al (2002). The authors used the DOCSIS model to simulate the behavior of the IEEE 802.16. According to the Webopedia Computer Dictionary ("What is DOCSIS?" webpage 2005), DOCSIS defines "interface standards for cable modems and supporting equipment.... DOCSIS specifies downstream traffic transfer rates between 27 and 36 Mbps over a radio frequency (RF) path in the 50 MHz to 750+ MHz range, and upstream traffic tranfer rates between 320 Kbps and 10 Mbps over a RF path between 5 and 42 MHz." The actual standard defines modulation schemes and a protocol for bidirectional communication over cable.

Ramachandran et al (2002) identified a number of similarities and differences between IEEE 802.16 and DOCSIS 1.1. More specifically, the DAMA-TDMA scheme is supported by both standards, the resolution contention mechanism is the same and both implementations share a number of common QoS features. The most important difference between the two standards is that IEEE 802.16 operates on a wireless PHY as opposed to the hybrid fiber-coax medium supported by DOCSIS. The authors proceeded in making changes to the DOCSIS PHY model in order to approximate the IEEE 802.16 PHY behavior. In our study, we decided to use the OPNET DOCSIS 1.1 model without alterations since this can be considered the closest MAC approximation available and it supports PTP connections just like IEEE 802.16. In other words, we consider this model to be good enough for the scope of this research. In addition, all the scenarios for the mesh clusters will use the same DOCSIS PHY model, so any errors should be introduced to all the scenarios.

2. OPNET Model Creation

In order to use the current OPNET DOCSIS model we had to create a node that would support both DOCSIS and IEEE 802.11 interfaces. The IEEE 802.11 interface is necessary for the node's communication with the mesh clusters. Our node was derived by the wlan_ethernet_router node and its name was wlan_ethernet_docsis_router (Figure 23). The derived node supports only fixed stations since this is dictated by the nature of the IEEE 802.16 stations.

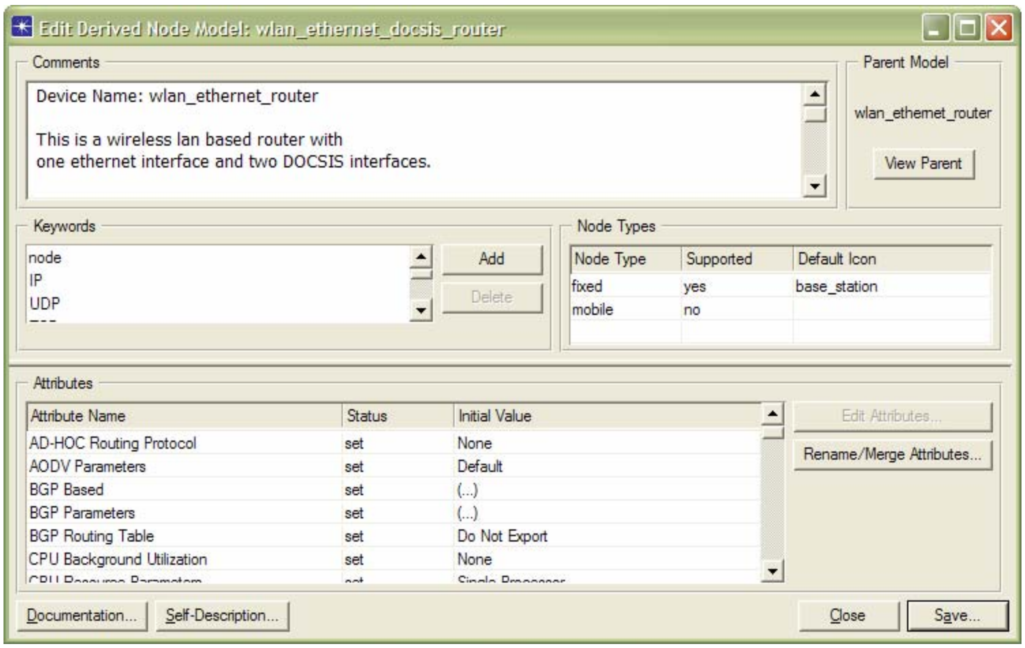

Figure 23. DOCSIS node derivation

The new node supported wireless LAN and Ethernet (inherited by the wlan_ethernet_router model), but did not have any DOCSIS interfaces. To add these interfaces, we had to input the necessary modules to the node model. These modules were available from the docsis2_slip8_gtw_adv node of the DOCSIS library. This process is illustrated in Figure 24.

The final model has the necessary wireless LAN and DOCSIS interfaces, so it is ready to be used as an IEEE 802.16 subscriber station.

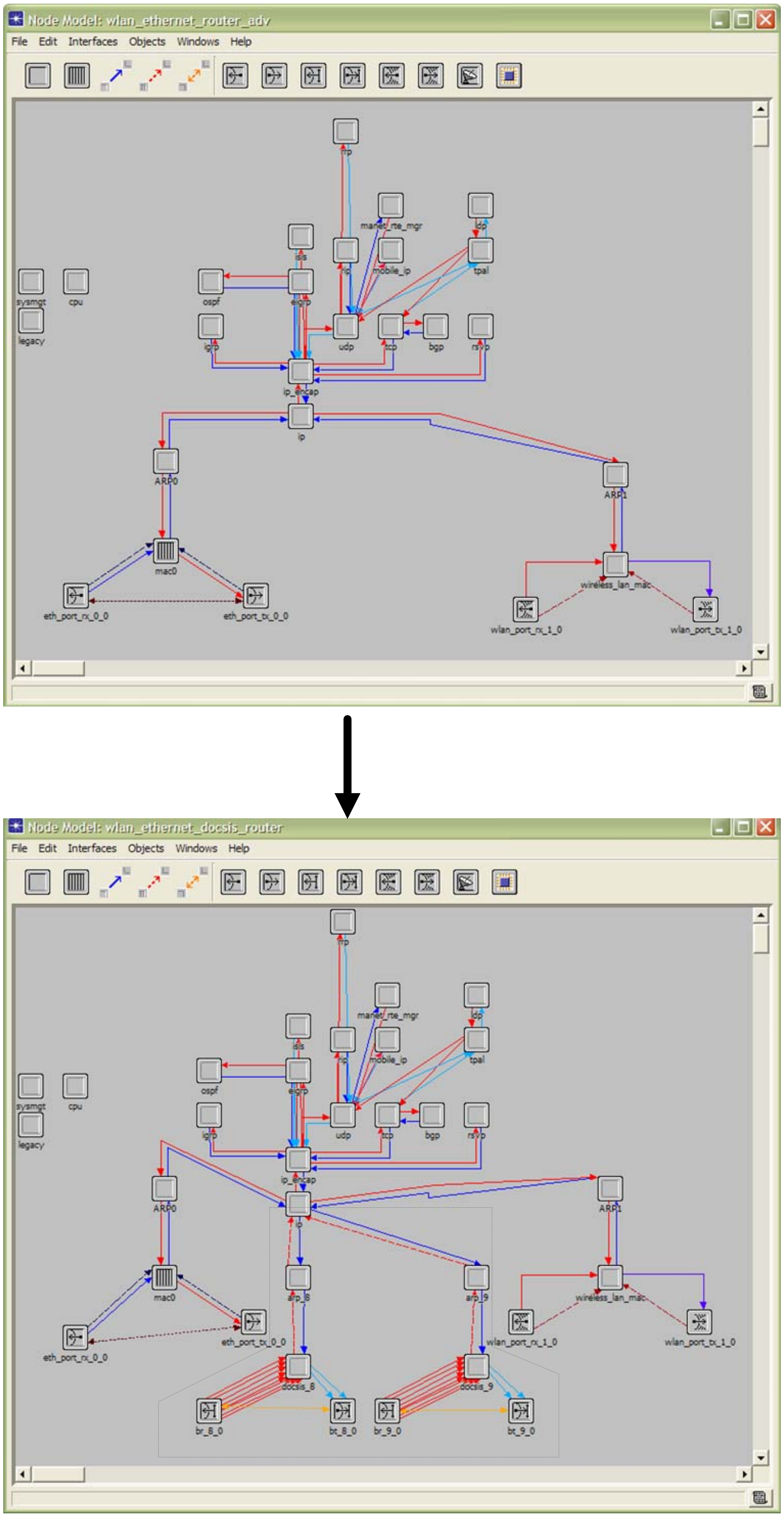

Figure 24. DOCSIS interfaces addition to node

D. SIMULATION OVERVIEW

Our simulation analysis is a performance evaluation study and this is the reason we chose to use the steps described in the systematic approach to performance evaluation by Jain (1991, 22). This approach provides the framework for describing performance projects and helps in avoiding common mistakes, such as no goal definition, biased goals and others. Some of the steps were omitted since they were obvious or irrelevant.

1. Goal Definition and System Description

The goal of this simulation is to identify an appropriate ad hoc routing protocol for our "environment" and potentially reveal a strong candidate for use in the TNT program. This "environment" includes two mesh clusters joined by two DOCSIS interfaces (Figure 25). As it was mentioned earlier, the role of the DOCSIS interfaces is to emulate the behavior of IEEE 802.16 links.

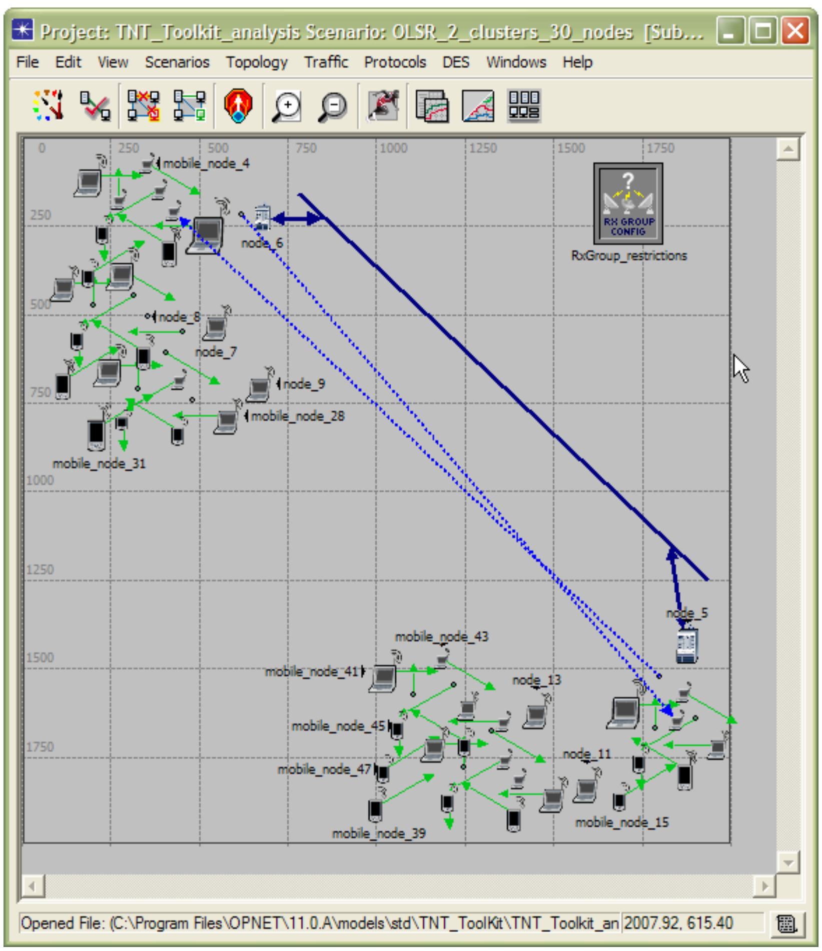

Figure 25. Simulation "environment" definition

2. Metrics

The selection of criteria to compare the performance of the routing protocols includes the following:

- Average routing traffic overhead. This is divided into two sub-metrics, namely average routing traffic sent and average routing traffic received.
- Average load on the wireless LAN interfaces of the mesh nodes.
- Average network throughput

3. Parameters

Jain (1991) divides the parameters that affect system performance into system and workload parameters. The system parameters include "both hardware and software parameters, which generally do not vary among various installations of the system" (Jain 1991, 23). Workload parameters are defined as "characteristics of users' requests, which vary from one installation to the next" (Jain 1991, 23). In our case, these parameters are illustrated in Table 2.

System Parameters	Workload Parameters
Speed of laptop CPU	Nodes' position in cluster
Battery capacity of laptop	Distances between nodes
Speed of PDA CPU	Distance between nodes and IEEE 802.16 router
Battery capacity of PDA	Number of mesh clusters
Laptop nodes' configuration (OS, interfaces)	Total number of nodes in each cluster
PDAs' configuration (OS, interfaces)	Number of fixed nodes per cluster
WLAN routers' configuration (OS, interfaces)	Number of PDA nodes per cluster
WLAN interfaces (802.11b supporting DSSS at 11Mbps)	Node application load
IEEE 802.16a BS and SSs configuration (70Mbps/ channel, maximum distance 30 miles)	Application demands between nodes

IEEE 802.11 receiver distance threshold (180 meters).	Mobility patterns
Type of routing protocol (OLSR, DSR, AODV)	

Table 2. System and workload parameters

Overall, we selected 2 clusters consisting of 50% mobile laptops, 30% PDAs and 20% fixed nodes. For the mobility parameter, we created 8 custom patterns (up, up-right, up-left, down, down-right, down-left, left and right) and we used all these patterns inside the mesh clusters (Figure 26).

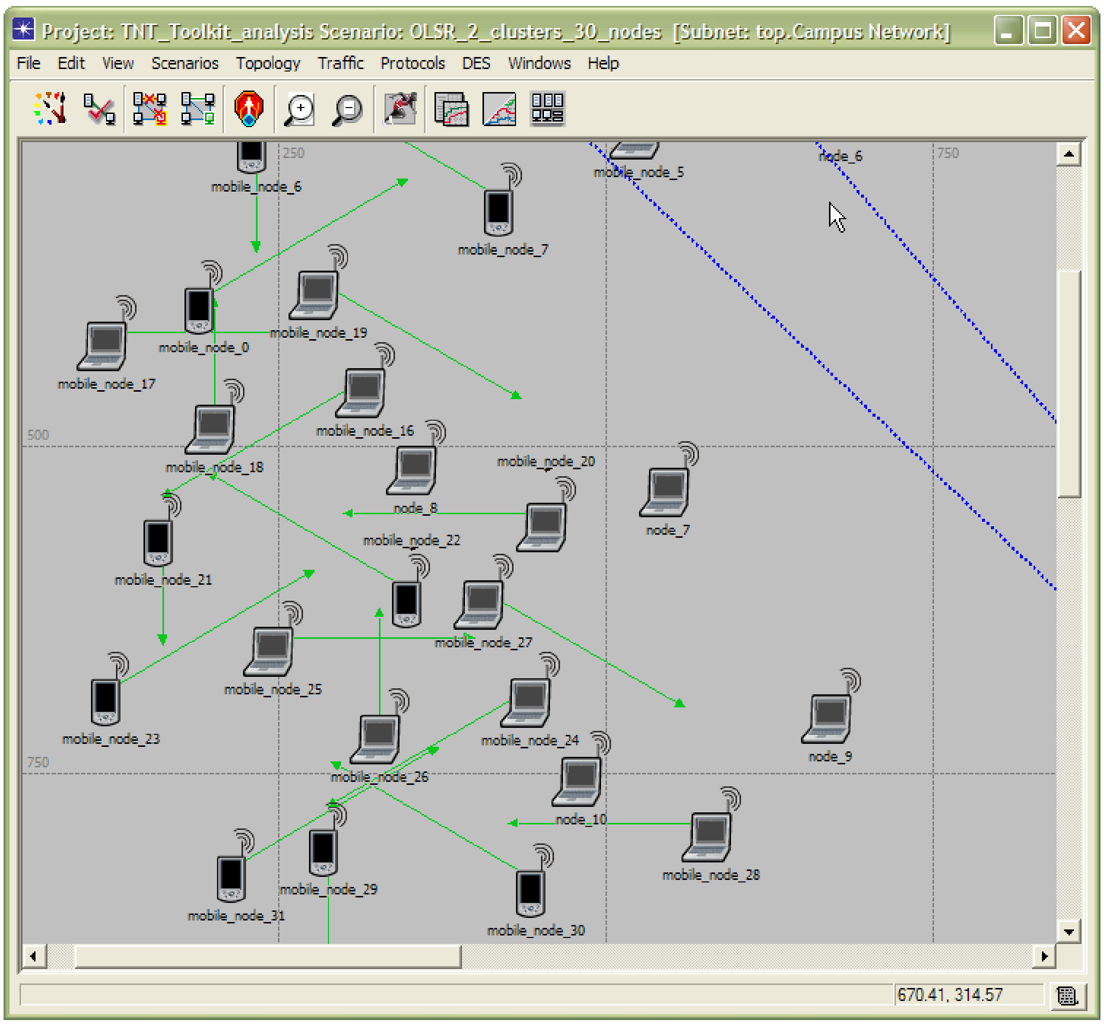

Figure 26. Mobility patterns

4. Factors

The parameters that we selected to vary during the simulation study and their corresponding levels are the following:

- Number of nodes in each mesh cluster. We chose two levels, namely 10-node clusters and 30-node clusters.
- Type of routing protocol, namely OLSR, DSR and AODV.

Overall, we selected two factors with two and three levels respectively.

5. Workload

We selected two types of workload for our scenarios. The first corresponds to raw traffic generation in each node of the mesh clusters. The characteristics of this traffic are shown in Table 3.

Parameter	Value
Start time	100 sec after simulation starts
Packet interarrival time (secs)	Exponential distribution with mean outcome 1 sec
Packet size (bits)	Exponential distribution with mean outcome 1024 bits
Destination IP address	Random
Stop time	End of simulation

Table 3. Individual node's traffic generation parameters

The second type is related to two IP layer traffic flows between two pairs of fixed nodes from each cluster. More specifically, we selected the IP_G711_Voice demand which represents VoIP traffic. In this way, we can simulate specific flows between the two mesh clusters (Figure 27).

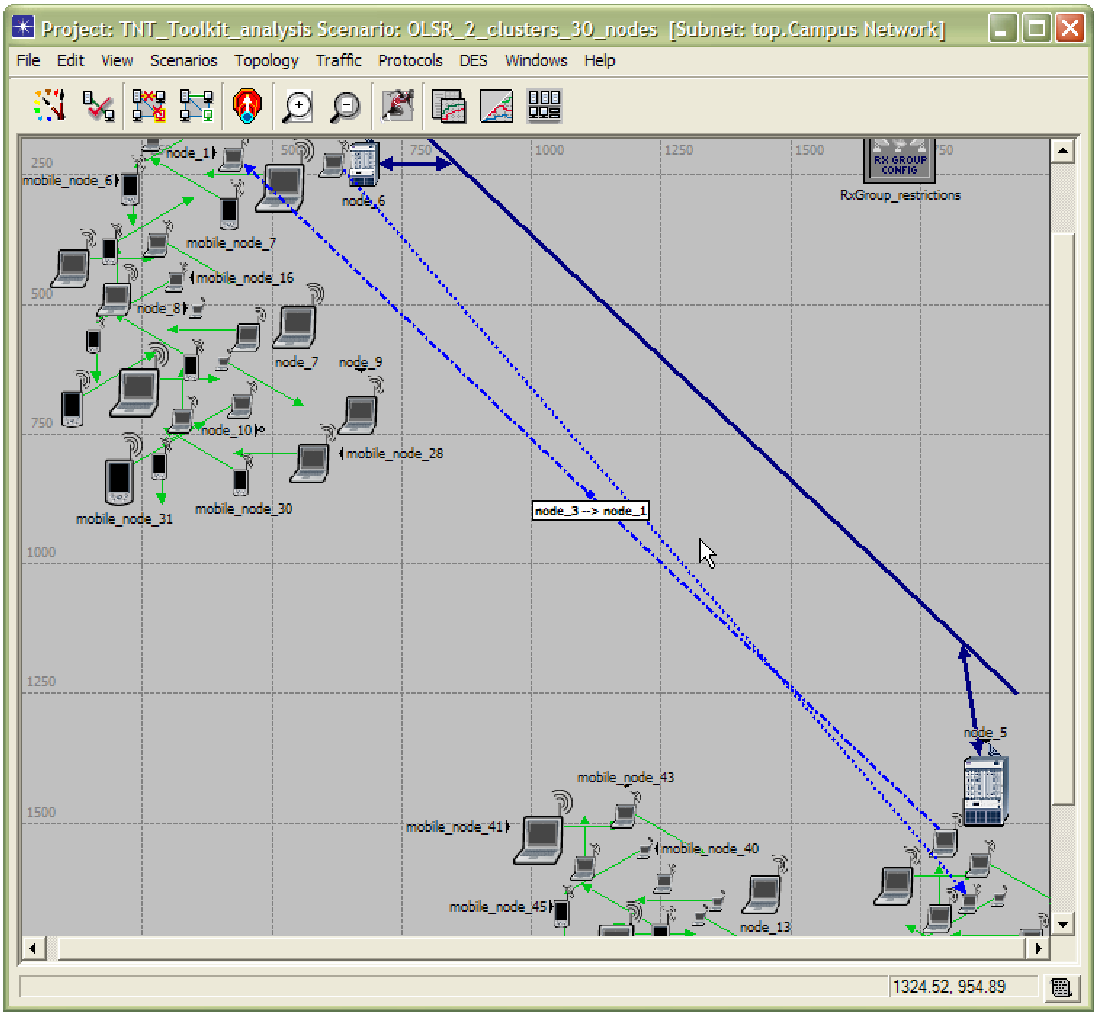

Figure 27. IP traffic flows between mesh clusters

6. Experimental Design

We selected a full factorial design with $2 \times 3 = 6$ runs in order to study all the possible combinations of the scenarios.

7. Data Presentation and Analysis

In the 10 node scenarios, all three protocols perform closely in the routing traffic sent overhead. The most dominant is AODV which demonstrates the lowest routing traffic overhead of 6Kbps, but the rest protocols are close with DSR at 15Kbps and OLSR at 12Kbps. This is not true for the routing traffic received overhead where OLSR exhibits a very high 44Kbps traffic. When we increase the number of nodes to 30, DSR is the most desirable with approximately 60Kbps traffic sent and 90Kbps traffic received. OLSR is the least desirable with 100Kbps traffic sent and 340Kbps traffic received, while

AODV performs well at traffic sent (48Kbps) but exhibits a higher traffic received overhead (130Kbps). The above information is illustrated in Figure 28. The routing traffic overhead reveals that in clusters with fewer nodes the reactive family (DSR and AODV) performs better than the proactive. This outcome is expected since the proactive protocols involve a standard background traffic to maintain current routing information. As we increase the number of nodes in each cluster, the proactive family exhibits a very high overhead since there are more nodes and more topological changes due to mobility patterns. In this case, the reactive family exhibits a 40% less traffic sent and more than 50% less traffic received overhead than the proactive. Based on these observations, the DSR and AODV are expected to perform better in the network as the number of nodes increase. If we would like to investigate further the routing overhead in the reactive family, we have to examine the route discovery time and the average number of hops per route (Figure 29). For the first parameter, AODV performs better since the discovery time stabilizes around 0.15sec after the first 10 minutes of simulation. For the second parameter, DSR and AODV perform similarly in the 10 node example, but when the number of nodes increases, the AODV algorithm seems to produce better results.

Overall, the reactive protocols perform better in regards to the routing traffic overhead and the way this overhead scales as the number of nodes increases. Between the two reactive protocols, AODV seems to be the more dominant since it exhibits lower route discovery time and smaller average number of hops per route.

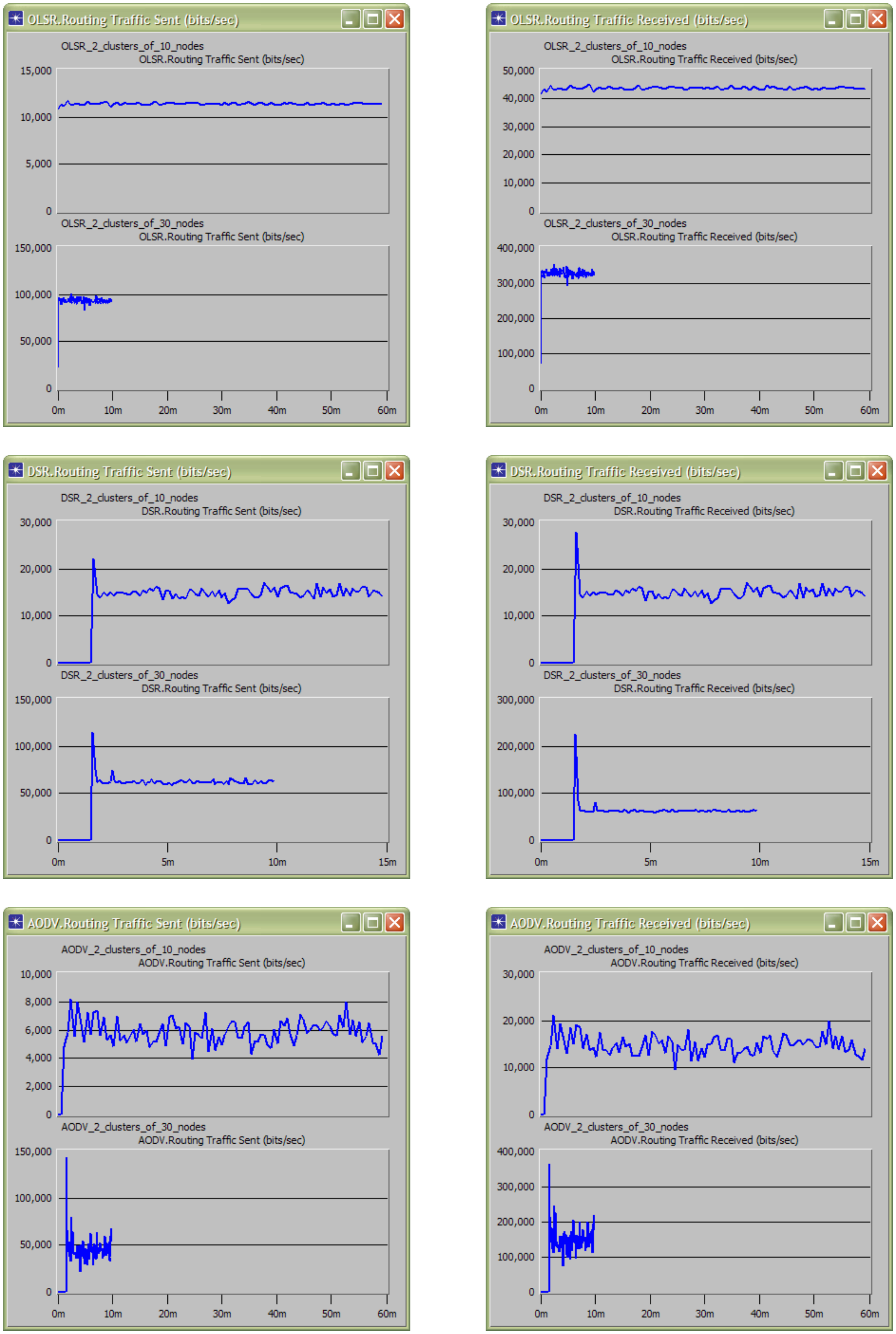

Figure 28. Routing traffic sent and received

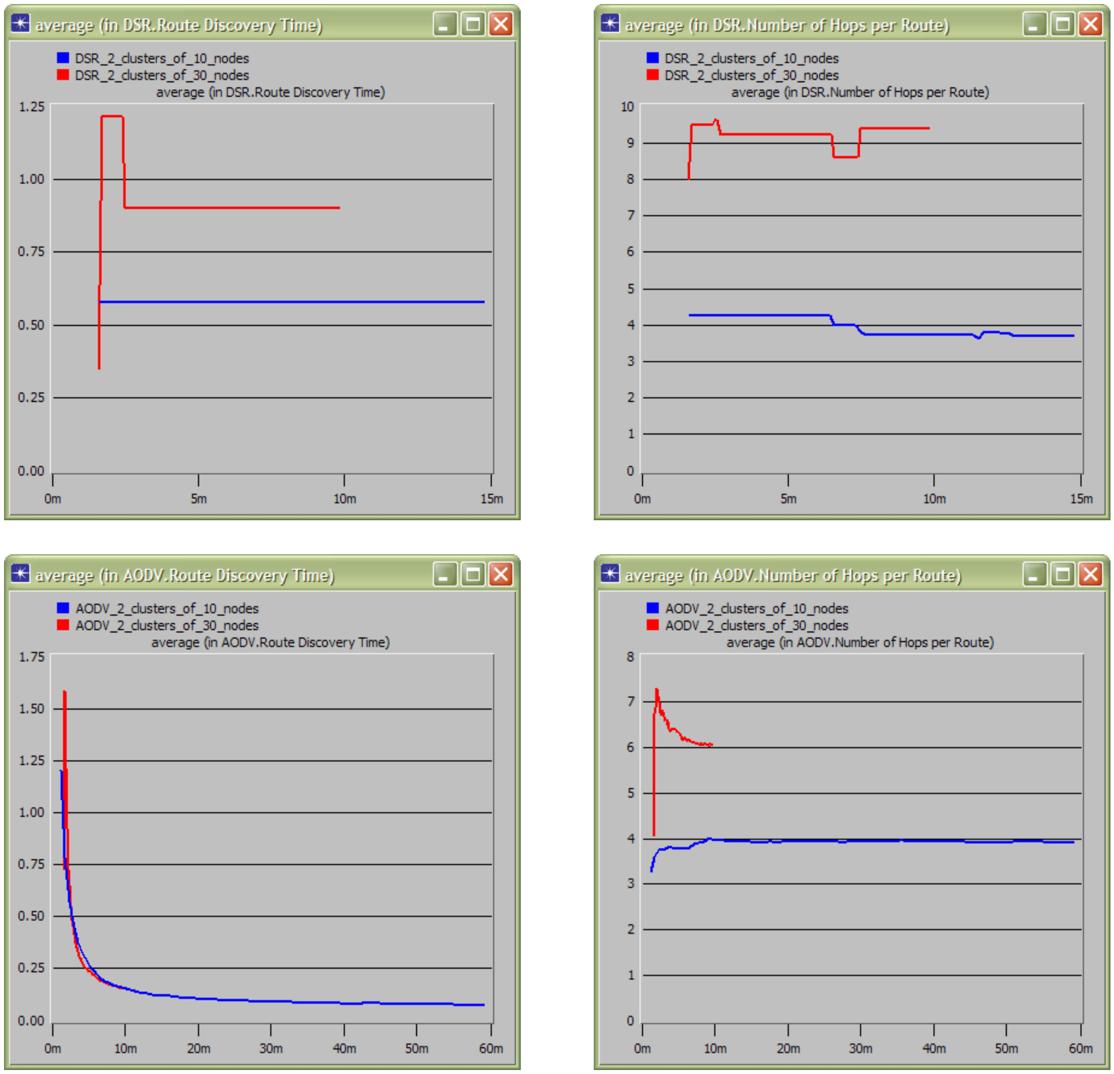

Figure 29. Route discovery time and average number of hops per route in reactive protocols

The load on the wireless LAN is important for the performance of the network. Figure 30 shows that OLSR performs better in the 10 node clusters and moreover, scales well when the number of nodes increases. Overall, OLSR generates 25% to 35% of the load that is present when DSR and AODV are used.

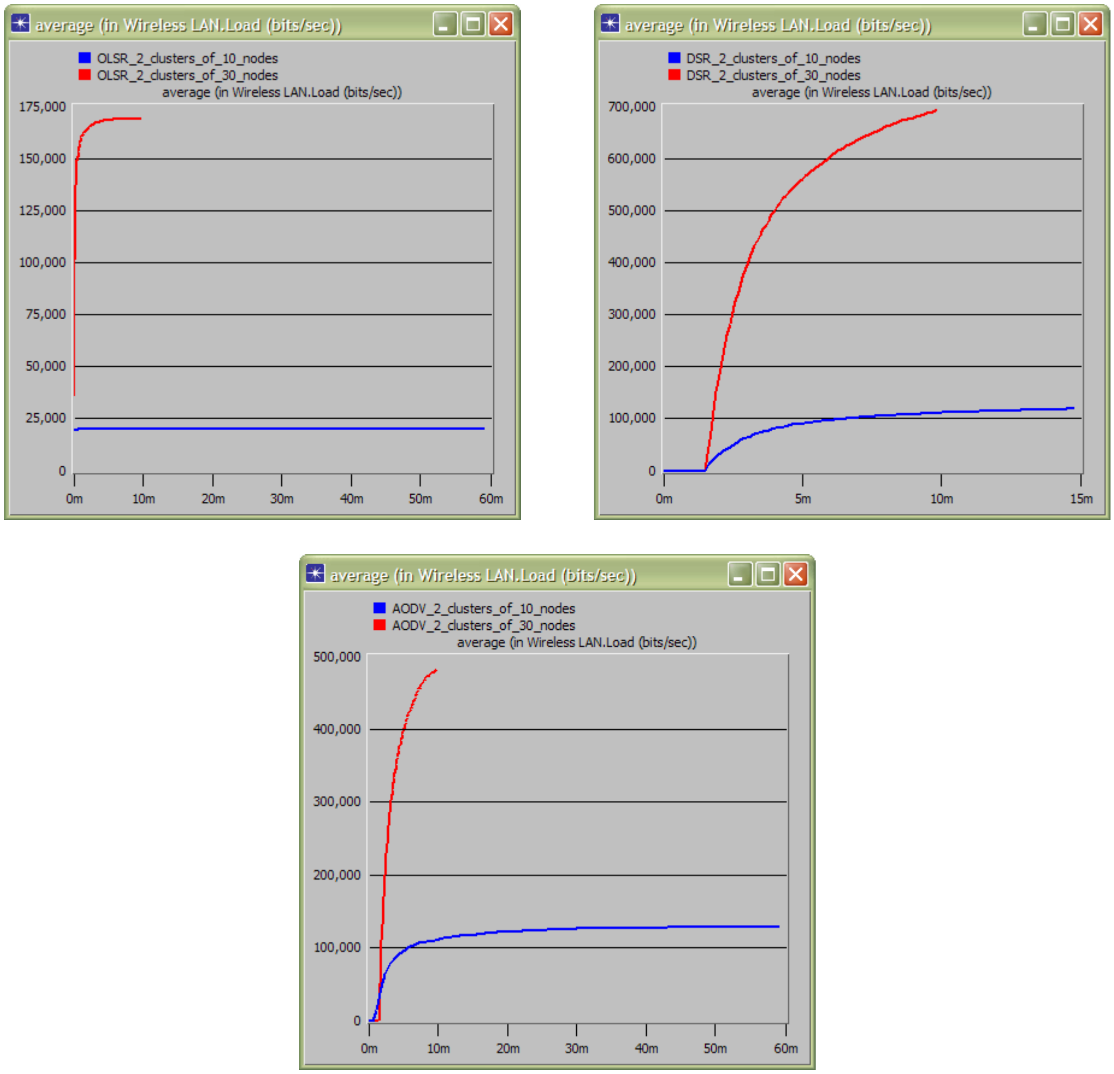

Figure 30. Average load on wireless LAN

The throughput parameter is considered crucial for the performance of a network. In our case, in the 10-node clusters all of the protocols demonstrate similar throughput (around 100Kbps). When the number of nodes increases, DSR shows the most promising results followed closely by OLSR and AODV (Figure 31).

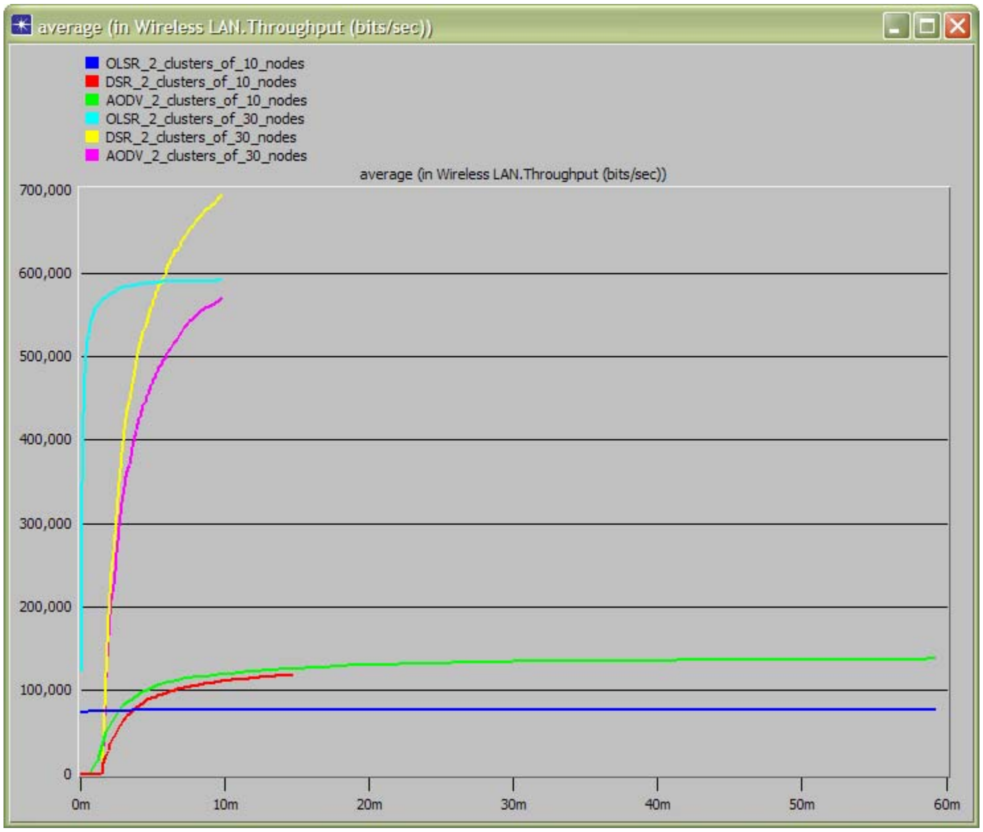

Figure 31. Throughput performance

Overall, the metrics do not identify a single dominant protocol for each scenario. Some of the protocols perform better in one metric at a give scenario and worse in others. If we had to choose a single answer, then this would have to be AODV. This protocol performs well in routing traffic overhead, it is second best in wireless LAN load and finally, it demonstrates good performance characteristics. OLSR is not a good choice because of the extensive routing traffic overhead and the poor scalability issues, while DSR demonstrates higher route discovery time, higher number of hops per route and the worst load characteristics.

E. CONCLUSION

The simulation analysis was focused on the specific needs of the TNT program. During our study we identified two important aspects. First of all, in order to analyze the behavior of the mesh clusters, we had to consider the IEEE 802.16 backbone. This is an integral part of the TNT program and also, provides the only way for mesh clusters interconnection. Secondly, since there is no known implementation of an OPNET 802.16

model, we had to search alternative solutions. We found that the most suitable candidate was the DOCSIS standard which is already integrated in OPNET.

The simulation analysis incorporated two scenarios for each protocol solution. The difference between the scenarios was the number of nodes included in each mesh cluster. We executed many simulation runs to identify specific metrics, parameters and factors that affected the simulation results. It turned out that each scenario was heavily influenced by the initial conditions, meaning nodes' position, distance between nodes, distance between mesh cluster and DOCSIS router, mobility patterns and traffic load. By changing some of these parameters, we produced completely new results for the performance of the protocols. In order to compensate for this effect, we had to define all the parameters in detail and identify specific scenarios. For these scenarios, the simulation analysis revealed that there is no best candidate for every scenario. One thing that was evident was that the reactive family of protocols exhibited better characteristics and addressed scalability issues more efficiently than the proactive approach. If we had to choose one protocol, then we would select AODV. This protocol performed particularly well in the routing traffic overhead and demonstrated good characteristics in the WLAN load and throughput.

Overall, the mesh toolkit can support the implementation of different TNT scenarios but the specifics of the simulation scenarios should be as close to reality as possible since there is a great dependency on the initial conditions.

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V. CONCLUSIONS

A. OVERVIEW

The purpose of this study was to implement a wireless mesh simulation toolkit and to determine the suitability of different families of ad hoc routing protocols for the TNT program. Mesh clusters demonstrate a number of characteristics that are highly desirable in military operations. These characteristics include a self-organizing and self-healing ability along with an adaptive and fault-tolerant nature, support for heterogeneity and increased network robustness. In the TNT environment, the modeling of these mesh clusters is quite important since the mesh toolkit can address scalability issues more effectively than actual experiments, it can provide a technique for verifying and validating the experimental results and finally, it can save time, effort and cost by running "what-if" scenarios in a simulation environment.

During the design phase of the modeling task we identified a number of issues that should be resolved in order to produce an appropriate model design. These issues included the proper selection of ad hoc routing protocols, simulation environment and types of nodes. We decided to incorporate OLSR, DSR and AODV in our design, to use OPNET environment and to model two types of nodes, namely laptops and sensors. Moreover, we had to identify the distinct characteristics of each node in order to succeed in the modeling task. For the laptop nodes these characteristics included wireless communications, sufficient processing power and battery life, adequate storage capability, mobility and support for fixed and mobile nodes. The sensors were described as wired and fixed nodes attached to a laptop which provided connectivity to the mesh cluster. Based on the above observations, we implemented a mesh network toolkit in OPNET. This toolkit included a number of OPNET utility files and models along with the nodes that we created to support the selected routing protocols.

The simulation analysis was focused on the specific needs of the TNT program. This required taking under consideration TNT's IEEE 802.16 backbone. Since there was no known model for IEEE 802.16 in OPNET, we decided to use the most appropriate alternative, namely the DOCSIS standard. The criteria for determining the suitability of

the different protocols for TNT were routing traffic overhead, wireless LAN load and throughput. Based on these criteria, we tested two different scenarios that involved 10-node and 30-node clusters. The simulation results revealed that there was a heavy dependency on initial conditions (nodes' position, distance between nodes, distance between mesh cluster and DOCSIS router, mobility patterns and traffic load) and that there was no single best protocol for every scenario. Overall, the reactive family of protocols exhibited the best characteristics and if we had to choose one protocol for the TNT mesh clusters, this would have to be AODV.

Finally, we concluded our analysis with the observation that the mesh toolkit can support the implementation of different TNT scenarios but the specifics of the simulation scenarios matter since there is a great dependency upon the experiment/ simulation's initial conditions.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

The modeling study and the simulation analysis of mesh clusters revealed a number of potential research topics that would benefit the TNT program. These include the following:

- Addition of other families of ad hoc routing protocols in the simulation toolkit. These protocols can be used in simulation scenarios to determine their effects on the TNT network.
- Modeling of power constrained devices such as PDAs. The power management issues and the behavior of these devices can greatly influence network performance.
- Modeling of sensor-specific protocols (for example, EAP) and integration in the ad hoc environment.
- IEEE 802.16 MAC and PHY modeling. This is crucial in simulating the actual TNT environment. Our approach used DOCSIS which is a simplified approximation of IEEE 802.16. A more robust and detailed analysis can only be achieved by incorporating this model to our existing simulation toolkit.
- Creation of simulation scenarios based on specific TNT experiments and comparison of results. In this case the crucial factor is the level of detail in the network representation since the simulation results depend on the initial conditions.

The study of these areas can enhance the simulation toolkit functionality and can provide helpful insights for the TNT program.

APPENDIX. FILES REMOVED FROM THE OPNET PROTOCOL PACKAGES

A. OLSR

A/A	Filename
1	MANET_OLSR_PROTOCOL.prj
2	MANET_OLSR_PROTOCOL-scenario1.cml
3	MANET_OLSR_PROTOCOL-scenario1.ef
4	MANET_OLSR_PROTOCOL-scenario1.nt.log
5	MANET_OLSR_PROTOCOL-scenario1.nt.m
6	MANET_OLSR_PROTOCOL-scenario1.seq

Table 4. Files removed from the OLSR protocol package

B. DSR

A/A	Filename
1	AFIT_DSR_MODEL.prj
2	AFIT_DSR_MODEL-Baseline_20src.ac
3	AFIT_DSR_MODEL-Baseline_20src.cml
4	AFIT_DSR_MODEL-Baseline_20src.ef
5	AFIT_DSR_MODEL-Baseline_20src.i0.nt.exp
6	AFIT_DSR_MODEL-Baseline_20src.i0.nt.lib
7	AFIT_DSR_MODEL-Baseline_20src.i0.nt.so
8	AFIT_DSR_MODEL-Baseline_20src.nt.m
9	AFIT_DSR_MODEL-Baseline_20src.pb.m
10	AFIT_DSR_MODEL-Baseline_20src.seq
11	AFIT_DSR_MODEL-Baseline_30src.ac
12	AFIT_DSR_MODEL-Baseline_30src.cml
13	AFIT_DSR_MODEL-Baseline_30src.ef
14	AFIT_DSR_MODEL-Baseline_30src.i0.nt.exp
15	AFIT_DSR_MODEL-Baseline_30src.i0.nt.lib

16	AFIT_DSR_MODEL-Baseline_30src.i0.nt.so
17	AFIT_DSR_MODEL-Baseline_30src.nt.m
18	AFIT_DSR_MODEL-Baseline_30src.pb.m
19	AFIT_DSR_MODEL-Baseline_30src.seq
20	AFIT_DSR_MODEL-VV_Model.ac
21	AFIT_DSR_MODEL-VV_Model.cml
22	AFIT_DSR_MODEL-VV_Model.ef
23	AFIT_DSR_MODEL-VV_Model.i0.nt.exp
24	AFIT_DSR_MODEL-VV_Model.i0.nt.lib
25	AFIT_DSR_MODEL-VV_Model.i0.nt.so
26	AFIT_DSR_MODEL-VV_Model.nt.m
27	AFIT_DSR_MODEL-VV_Model.pb.m
28	AFIT_DSR_MODEL-VV_Model.seq
29	AFIT_DSR_MODEL-VV_Model_20src.ac
30	AFIT_DSR_MODEL-VV_Model_20src.cml
31	AFIT_DSR_MODEL-VV_Model_20src.ef
32	AFIT_DSR_MODEL-VV_Model_20src.i0.nt.exp
33	AFIT_DSR_MODEL-VV_Model_20src.i0.nt.lib
34	AFIT_DSR_MODEL-VV_Model_20src.i0.nt.so
35	AFIT_DSR_MODEL-VV_Model_20src.nt.log
36	AFIT_DSR_MODEL-VV_Model_20src.nt.m
37	AFIT_DSR_MODEL-VV_Model_20src.pb.m
38	AFIT_DSR_MODEL-VV_Model_20src.seq
39	AFIT_DSR_MODEL-VV_Model_30src.i0.nt.exp
40	AFIT_DSR_MODEL-VV_Model_30src.i0.nt.lib

Table 5. Files removed from the DSR protocol package

C. AODV

A/A	Filename
1	NIST_AODV-40_node_network.ac
2	NIST_AODV-40_node_network.nt
3	NIST_AODV-40_node_network.nt.m
4	NIST_AODV-40_node_network.pb.m
5	NIST_AODV-40_node_network.s1.nt.so
6	NIST_AODV-40_node_network.seq
7	NIST_AODV-40n_20src.os
8	NIST_AODV.prj

Table 6. Files removed from the AODV protocol package

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